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Mechanistic Liquid State Thermochemical Decomposition of Neat 1,3,5,5-Tetranitrohexahydropyrimidine (DNNC) and Its DNNC-d₂, DNNC-d₄, DNNC-d₆ Structural Isotopomers: Entering the DNNC Molecule¹ (Preprint)

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Abstract

Global kinetics for the liquid state thermochemical decomposition of neat 1,3,5,5-tetranitrohexahydropyrimidine (DNNC), perdeuterio-labeled DNNC-d₆, and partially deuterium-labeled DNNC-d₂ and DNNC-d₄ isotopomers were obtained by isothermal differential scanning calorimetry (IDSC). Molecular kinetic deuterium isotope effect (KDIE) values obtained with DNNC and DNNC-d₆ from 174 to 194 °C revealed that C-H bond rupture regulates both an endothermic catalytic initiation and the exothermic propagation of the liquid thermochemical decomposition process. Using IDSC-based KDIE comparisons with the DNNC-d₂, DNNC-d₄, and DNNC-d₆ isotopomers, a more detailed chemical structure/mechanistic relationship emerged by entering the interior of the DNNC molecule. Here structure kinetic KDIE results showed the rate-controlling C-H bond rupture has its origin at the non-equivalent C-2 methylene group sandwiched between the two nitrated DNNC nitrogen ring atoms, versus at the chemically equivalent C-4 and C-6 methylene ring positions located elsewhere in the DNNC structure. Elucidation of such mechanistic features should aid in the structural design of new high energy compounds with improved thermochemical properties. A 170.0 kJ/mol activation energy appeared for the endothermic induction period, and a lower 104.2 kJ/mol activation energy was determined for the exothermic acceleratory portion of the DNNC decomposition process. The global neat liquid and solid state thermochemical decomposition processes for DNNC also are compared.

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Introduction

Although complex global reaction kinetics, obtained by relatively inexpensive thermal analysis methods, often are ignored in favor of highly-defined individual kinetic steps requiring more sophisticated and expensive equipment,³ global kinetics data can describe complex thermochemical decomposition processes in ways which critically impact practical technology and safety concerns.^{3,4} For example, isothermal differential scanning calorimetry (IDSC) global kinetics rate constants, determined for the solid state thermochemical decomposition of 1,3,5-triamino-2,4,6-trinitrobenzene (TATB), accurately predict the 354 °C experimentally determined critical temperature which initiates a thermal explosion event.⁵

The condensed phase neat thermochemical decomposition process an energetic compound follows is primarily a complex mechanistic set of interacting intermolecular bimolecular reactions⁶ with some degree of intramolecular unimolecular character. Generally, two key chemical bond ruptures occur during the thermochemical decomposition process. The first is the **initial homolytic bond rupture** (scission or cleavage) which determines the specific pathway the decomposition process will follow and the resultant product composition. Certain structural arrangements in an energetic molecule (*eg.* N-NO₂ for secondary nitramines)⁷ are centers (explosophores) for this initial bond rupture which often are termed the “trigger linkage,” or more recently, the “first reaction”.⁸ Once this specific pathway is established, a myriad of subsequent chemical reaction channels proceed which occur in series and competing parallel sequences. Along this reaction pathway, one chemical reaction in a specific reaction channel proceeds more slowly than all others. It is during this slow reaction that the second critical homolytic bond rupture occurs which significantly regulates the overall rate at which this slowest reaction channel and the entire decomposition process proceeds. This subsequent KDIE-determined **rate-controlling chemical bond rupture**, accompanied by a concomitant atom transfer,⁹ usually occurs early in the thermochemical decomposition process.^{4,10,11} and can be determined *in-situ* using the kinetic deuterium isotope effect (KDIE) approach in conjunction with ambient pressure isothermal

DSC,^{4,5,10-12} reaction quenching,¹² and TGA¹³ analyses. If this slowest reaction did not exert a significant impact on the overall global decomposition rate, a noticeable KDIE would not be observed.

This critical rate-controlling bond rupture has been determined for the ambient pressure thermochemical decomposition processes of TNT,¹¹ TATB,⁵ HMX,^{9,13} and RDX.^{12,13} In every case, the same mechanistic rate-controlling bond rupture found in the ambient pressure decomposition process for each compound, proved to be a significant rate-controlling mechanistic feature observed in rapid deflagration,^{9,16} high-pressure combustion,^{14,15,16} and thermal explosion events.^{5,16} Furthermore, it is detected as being a significant contributing mechanistic feature in impact or shock explosive initiation sensitivity.^{13,16-23} Identification of the pathway directing initial bond rupture, of the subsequent rate-controlling bond rupture, and of the resultant product composition formed during the thermochemical decomposition processes are critical for obtaining energetic compounds with improved thermochemical and initiation sensitivity properties.

The first KDIE approach applied to the thermochemical decomposition of an energetic compound occurred with neat liquid TNT and TNT- α -d₃.¹¹ IDSC analysis during the TNT endothermic induction period, the earliest portion in the thermochemical decomposition process, revealed that C-H bond rupture in the pendant TNT methyl group controls the formation of a catalytic species, which upon reaching a minute threshold concentration, initiates the TNT exothermic acceleratory phase and a concomitant energy release. A subsequent KDIE study with solid state TATB and TATB-d₆ found that N-H bond rupture also constituted the rate-controlling mechanistic feature early during the thermochemical decomposition process.⁵

The seminal KDIE-based thermochemical decomposition investigation of a heterocyclic nitramine was accomplished with HMX and HMX-d₈ and revealed a different KDIE and rate-controlling mechanistic step dependence on the HMX physical state.⁹ This IDSC study showed a rate-controlling C-H bond rupture occurred during solid state decomposition along with other rate-controlling features in the mixed-melt and liquid state decompositions. Proposed was an initial N-NO₂ bond rupture to form

the NO₂ radical which then, either, unimolecularly from an HMX radical intermediate existing in a proposed cage effect,²⁴ or bimolecularly from a neutral HMX molecule, transfers a hydrogen atom via NO₂ radical abstraction to form the unstable HONO species.⁹ This unstable species undergoes further decomposition to form other oxidizing and catalytic species,⁹ such as NO, NO₂, and H₂O, or in some cases, possibly OH and NO,²⁵ while resultant HMX radicals continue along various decomposition reaction channels and condensed phases.⁹

This rate-controlling C-H bond rupture for solid state HMX was confirmed by a subsequent HMX/HMX-d₈ isothermal TGA decomposition study.¹³ Later, a more detailed mechanistic isothermal pyrolysis investigation with HMX and HMX-d₈ was conducted using simultaneous thermogravimetric modulated beam mass spectrometry (STMBMS) where different reaction channels of specific product specie formation, during the decomposition process, could be measured concurrently.^{26,27} At least four different reaction channels were identified, and a large KDIE was found for water product formation. Finding a large KDIE for water formation also was consistent with an initial N-NO₂ bond cleavage, a subsequent rate-controlling methylene C-H bond rupture and hydrogen atom transfer from an HMX species to form the unstable HONO molecule⁹ and its decomposition to the water byproduct. Water, occluded in the HMX crystal structure, also was suggested as a hydrogen atom donating catalyst for another reaction channel.²⁷ Conceivably, the water product, formed via the KDIE measured rate-controlling C-H bond rupture outlined above, also could contribute to the water catalysis channel.

The same rate-controlling C-H bond rupture was identified for the liquid state thermochemical decomposition of RDX and RDX-d₆ using isothermal TGA.¹³ This result was further verified by a subsequent IDSC and a UV-based reaction quenching KDIE study.¹² A later STMBMS RDX/RDX-d₆ investigation revealed a complex multi-channeled liquid thermochemical decomposition process which was different from HMX, but still revealed a rate-controlling C-H bond rupture, and atom transfer from the RDX methylene group, both being highly prevalent mechanistic features.^{25,28,29} In fact, it appears

the progression **rate** of all four reaction channels may depend upon C-H bond rupture in the first channel.

While much more thermally stable than the RDX, the cyclic DNNC nitramine derivative (Figure 1) undergoes extensive solid state thermochemical decomposition during long-term exposure in the 142 to 148 °C temperature range.⁴ IDSC-based KDIE results suggest that ring C-N bond rupture for the solid state decomposition likely is the rate-controlling bond rupture during the long endothermic induction period, wherein a catalytic species likely forms, and upon reaching a threshold concentration, initiates an autocatalytic exothermic acceleratory phase. Once the acceleratory phase is initiated, C-H bond rupture is the rate-controlling mechanistic feature which regulates its energy release rate. The endothermic induction period for the solid state decomposition process has a higher activation energy of 128 kJ/mole compared to the 115 - 106 kJ/mole^{1a,4} determined for the exothermic acceleratory phase. This supports the likely formation of a catalytic species from the DNNC molecule during the solid state induction period and mirrors the thermochemical behavior followed by the neat liquid TNT thermochemical decomposition process.¹¹

The relationship of the mechanistic rate-controlling homolytic bond rupture found in ambient pressure thermochemical decomposition processes to higher temperature, higher pressure catastrophic events such as deflagration, combustion, thermal explosion, detonation, and to energetic compound sensitivity issues, is well documented.^{10,16} Given the importance of this high energy rate-controlling mechanistic feature, the thermochemical decomposition of neat liquid DNNC, and its three isotopomers, DNNC-d₆, DNNC-d₄, and DNNC-d₂, was investigated by isothermal DSC to determine the rate-controlling homolytic bond rupture and its location in the DNNC molecular structure. Similarities and differences between this neat liquid state DNNC thermochemical decomposition process, and the previously reported mechanistic solid state DNNC thermochemical decomposition investigation,⁴ also are compared.

Experimental Section

Caution! Although reasonably stable to accidental explosive initiation, DNNC is a high energy explosive material. Care should be taken to use proper laboratory shielding and safety procedures in all handling and transfer operations.

Isothermal DSC Analysis. All isothermal DSC measurements were made with a Perkin-Elmer DSC 7 instrument described previously⁴ using DNNC sample sizes ranging from 1.50 to 1.53 mg. Prior to conducting the thermochemical decomposition runs, the DSC 7 temperature was calibrated at a 1 deg K/minute scanning rate using a two-temperature calibration procedure with indium (mp. 156.60 °C) and tin (231.88 °C) standards. The temperature of the DNNC sample (mp = 154.8-156.2 °C)³⁰ was stabilized to 30 °C under the nitrogen gas atmosphere and then was brought to its pre-determined isothermal decomposition temperature (174, 178, 182, 186, 190, or 194 °C) at a 480 °C per minute heating rate.

Isothermal DSC Data Reduction. The length of the endothermic induction period, and resultant induction times, were visually determined from individual thermograms generated for each IDSC run. The minute units were then converted to seconds for the calculations used to obtain activation energy and KDIE values. For determining the exothermic acceleratory phase rate constants, software programs were written at our laboratory to transfer the data from each designated IDSC run to a separate PC station, and then, to input the data into an autocatalytic kinetics plot program that used the $\delta\alpha/\delta t = k\alpha(1-\alpha)$ autocatalytic rate equation, where α is the mole fraction of decomposed DNNC at any given time (t). A software program, based on that developed at the Los Alamos National Laboratory,³¹ was used and is described in detail elsewhere.^{4,9}

Synthesis of DNNC and the DNNC-d₆, DNNC-d₄, and DNNC-d₂ Structural Isotopomers . The synthesis of ADIOL and ADIOL-d₄ (2,2-dinitropropane-1,3-diol-1,1,3,3-d₄) reactants, needed to obtain DNNC and its DNNC-d₆ analogue, was previously described.³² The partially deuterium-labeled DNNC-d₂ and DNNC-d₄ compounds were synthesized using an identical Mannich condensation reaction procedure, and scaled as needed, by employing the appropriate choice of unlabeled or deuterium labeled 2,2-dinitropropane-1,3-diol (ADIOL and ADIOL-d₄) and formaldehyde or formaldehyde-d₂, plus unlabeled *tert*-butylamine in methanol solvent. These initial Mannich condensation reactions provided the DBNP-d₂ and DBNP-d₄ intermediate compounds which were then converted to their respective final DNNC-d₂ and DNNC-d₄ products by 100% anhydrous nitric acid nitration. All ¹H NMR (acetone-d₆, TMS std.), mass spectral, FTIR (Kubelka/Munk) powder analyses and melting points for DBNP-d₂, DBNP-d₄, DNNC-d₂ (155-157 °C), and DNNC-d₄ (155-156 °C) were consistent when compared with previously reported values for the unlabeled DBNP, and DNNC analogues.³² Yields obtained for DBNP-d₂ and DBNP-d₄ compounds were similar to DBNP (75%) and DBNP-d₆ (72%). Final product yields for DNNC-d₂ (63%) and DNNC-d₄ (75%) compared well with DNNC (72%) and DNNC-d₆ (71%).³² Within the accuracy and precision of ¹H NMR integration values, the intermediate DBNP-d₂ reflected an incorporation of 2.2 methylene deuterium atoms; DBNP-d₄ incorporated 4.0 methylene deuterium atoms; and, 5.9 methylene deuterium atoms were incorporated into the DBNP-d₆ molecule relative to the two unlabeled *tert*-butyl groups substituted on the ring nitrogen atoms at the 1- and 3-ring positions. Because of the synthesis method used,³² the -CD₂- labeled methylenes were incorporated into the DNNC ring structure as a discreet unit; mixed -CHD- methylenes could not form. Proton NMR integrations of the two different methylene groups (δ 6.30 C-2 and δ 5.47 C-4 & C-6) for **both** DNNC-d₄ and DNNC-d₂ remained in a 1:2 integration ratio,

respectively, indicating a random distribution of the labeled $-\text{CD}_2-$ deuterium-labeled methylene groups occurred at all three C-2, C-4, and C-6 ring positions. In spite of this randomized $-\text{CD}_2-$ methylene distribution, relevant mechanistic information was obtained by comparing DNNC, DNNC- d_2 , DNNC- d_4 , and DNNC- d_6 IDSC isotopomer induction times and rate constants.

Results and Discussion

The **initial homolytic bond rupture** of an energetic material controls the reaction pathway, the number of reaction channels, the decomposition products, and the product composition of a thermochemical decomposition process. Later **rate-controlling homolytic bond rupture** ultimately controls the overall energy release rate during the decomposition of a given energetic material. Improved thermochemical properties must start with decreasing the rate at which a decomposition process proceeds, either kinetically, or by chemical structure alteration. An excellent example of possible progress is found in the chemical structure similarity and differences which exist between the symmetrical RDX cyclic nitramine molecule and the unsymmetrical DNNC cyclic pseudo-nitramine (Figure 1). This led us to investigate the solid and liquid state decomposition of 1,3,5,5-tetranitrohexahydropyrimidine (DNNC) pseudo-nitramine^{1,4} for comparison with RDX.

First synthesized in 1984,³³⁻³⁵ the DNNC molecule, is a unique heterocyclic hybrid structure which contains structural features found in both saturated cyclic nitramines (RDX and HMX) and in aliphatic geminal-dinitroalkyl compounds (Figure 1). While RDX contains three chemically equivalent ($-\text{CH}_2-$) methylenes, the DNNC structural variation provides three methylene ($-\text{CH}_2-$) groups where only two are chemically equivalent. Of the three DNNC methylenes situated at the C-2, C-4, and C-6 positions, the two methylene groups at the C-4, and C-6 positions, adjacent to the geminal dinitro-substituted C-5 carbon [$-\text{C}(\text{NO}_2)_2-$], are in a chemically equivalent environment like that found in RDX, but the third

DNNC methylene group at the C-2 position, sandwiched between the two nitrated ring N atoms (=NNO₂), is chemically non-equivalent with respect to the C-4 and C-6 methylene positions.

Insert Figure 1

Because of this structural variation, DNNC thermochemical stability resembles that of TNT, rather than its structurally related RDX and HMX nitramines, but does provide an explosive energy output which rivals RDX.⁴ Like TNT (mp = 80.0 to 81.2 °C)¹¹, neat DNNC melts without noticeable decomposition when heated above its 154.8 to 156.2 °C melting point; thus, a 5.19 kcal/mole (21.72 kJ/mol) DNNC heat of fusion could be determined by DSC analysis³⁰ (TNT ΔH_{fusion} = 5.34 kcal/mol or 22.34 kJ/mol)³⁶. Related cyclic nitramines RDX and HMX melt, or undergo liquefaction, with decomposition rapidly enough that their heat of fusion cannot be obtained. Additionally, DNNC and RDX structural variation affects thermochemical properties related to rapid pyrolysis and simulated combustion behavior.^{6, 37}

The liquid state thermochemical decomposition process for both DNNC and DNNC-d₆ was conducted at 4 °C temperature intervals from 174 °C to 194 °C using isothermal differential scanning calorimetry (IDSC). Each DNNC and DNNC-d₆ IDSC run provided a thermogram curve displaying three main features: (1) an endothermic induction period, (2) followed by the initiation of an exothermic acceleratory phase which, after reaching a maximum energy release at the thermogram peak, (3) entered into a decreasing exothermic decay phase until complete decomposition resulted. Ample thermogram curve shifts between each IDSC thermogram were obtained at the six isothermal temperatures (174, 178, 182, 186, 190, and 194 °C) selected for relevant kinetic evaluation (Figure 2).

Insert Figure 2

Thermochemical Physical and Kinetic Properties. Within this 20 °C temperature regime (174 – 194 °C), post IDSC sample weights of decomposed neat liquid DNNC showed an average 81% mass loss from conversion to gaseous products (Table 1). The remaining 19% of the DNNC sample was

converted to solid phase residue product(s) and remained in the sample pan. The liquid DNNC-d₆ decomposition process gave a nearly identical weight loss average of 80% with a 20% solid phase residue (Table 2). For comparison, solid state DNNC thermochemical decomposition afforded a 76% mass loss and solid state DNNC-d₆ a slightly smaller 73% mass decrease. Formation of a solid phase residue has very important implications in IDSC kinetic data evaluation.

Post solid phase residue can mean that intermediate derivatives form during the thermochemical decomposition process which react further until decomposition is complete. Two problems can result, and both can cause a misinterpretation of the KDIE value and its associated kinetics. First, kinetic evaluation may provide a combined rate constant value to which decomposition of the subject compound and further decomposition of the intermediate condensed phase derivatives both contribute. This results in a KDIE value which is diluted or reduced from the true value of the subject compound. Secondly, this rate constant may reflect data from decomposition of the condensed phase derivatives only formed from the initial energetic compound. In this case, the KDIE value offers no useful information about the original energetic compound and its decomposition process. These two related problems are amply documented in IDSC thermochemical decomposition investigations with liquid TNT^{10,11} and solid TATB.^{5,10} When the presence of condensed phase products appear, only the early portion of the thermochemical decomposition process, and the corresponding thermogram portion, should be evaluated, notably, the endothermic induction period and the exothermic acceleratory phase.

The DNNC and DNNC-d₆ thermochemical decomposition process afforded smooth thermograms that followed an autocatalytic rate behavior during a large portion of the exothermic acceleratory phase (Figure 2). The obvious incremental rate increase as one proceeds to higher temperatures, is visually depicted with decreasing induction times (t_i) and steeper (faster) acceleratory phase portions reflecting a higher rate constant (k). The percent of the acceleratory phase that could be fitted linearly to the autocatalytic rate plot, the exceptional least squares linear curve fits (R^2) obtained, and the corresponding rate constants (k) determined from the slopes of the linear portion of the autocatalytic

rate plot at each temperature, are found in Table 1. The rate constants shown at each isothermal temperature are averaged over at least five runs. Figure 3 illustrates the conversion of one thermogram run at 182 °C into its autocatalytic rate plot. Analogous data for DNNC-d₆ appear in Table 2. At a liberal 99% Student t variation analysis, each rate constant is unique and does not overlap with ones at adjacent temperatures. The heat of decomposition for both DNNC and DNNC-d₆ give similar values.

Insert Figure 3

Compared to the solid state DNNC thermochemical decomposition process,⁴ both the induction period and acceleratory phase kinetics proceed much faster above the 154.8 to 156.2 °C DNNC melting point. For example, the 184 min (11,040 s) induction time for solid state DNNC at 148 °C is nearly 7.5 times longer than the 148 s for liquid state DNNC at 182 °C. For the liquid state DNNC acceleratory phase at 182 °C, the rate constant seen in Table 1 is slightly over one order magnitude faster than the $3.38 \times 10^{-4} \text{ s}^{-1}$ rate constant obtained at 148 °C for solid state DNNC.⁴ The liquid state DNNC thermochemical decomposition releases heat energy much more rapidly than does the solid state process.

Table 1.^a Physical and Kinetic Properties of Neat Liquid DNNC Thermochemical Decomposition

temp. (°C)	induction time (s)	rate constant ($\text{k} \times 10^{-3} \text{ s}^{-1}$)	k linearity (%) ^b	$\Delta H_{\text{decomp.}}$ (kJ/mol)	wt. loss (%)	no. runs
194	52.6 ± 28.3	12.15 ± 0.48	68	-802.5 ± 48.5	80 ± 2	8
190	72.2 ± 19.3	9.61 ± 0.43	83	-775.3 ± 56.9	82 ± 4	5
186	93.8 ± 17.5	7.55 ± 0.64	94	-801.6 ± 30.1	82 ± 4	5
182	148.4 ± 13.8	5.87 ± 0.39	95	-786.6 ± 38.1	80 ± 5	5
178	228.6 ± 76.4	4.58 ± 0.25	94	-799.1 ± 61.1	80 ± 7	5
174	359.6 ± 153.7	3.45 ± 0.16	95	-803.3 ± 38.1	80 ± 3	5
ave.	-----	-----	-----	-795.0 ± 45.6	81 ± 4	---

^a All data variances computed at the 99% Student t level.

^b Percent of thermogram exothermic acceleratory phase fitting linear portion of the autocatalytic rate plot at a 0.999 least squares value (R^2)

Table 2.^a Physical and Kinetic Properties of Neat Liquid DNNC-d₆ Thermochemical Decomposition

temp. (°C)	induction time (s)	rate constant(k x 10 ⁻³ s ⁻¹)	k linearity (%) ^b	ΔH decomp (kJ/mol)	wt. loss (%)	no. runs
194	73.6 ± 35.1	7.16 ± 0.89	57	-766.5 ± 36.4	80 ± 3	6
190	126.5 ± 28.3	5.94 ± 0.45	72	-797.9 ± 119.7	84 ± 12	5
186	169.9 ± 39.5	4.71 ± 0.35	81	-777.8 ± 81.2	81 ± 4	6
182	274.0 ± 59.6	3.58 ± 0.19	82	-767.8 ± 53.3	81 ± 6	5
178	437.4 ± 120.6	2.76 ± 0.29	82	-754.8 ± 25.1	81 ± 4	5
172	652.0 ± 82.2	2.06 ± 0.10	83	-769.0 ± 24.3	77 ± 1	5
ave. value	-----	-----	-----	-772.4 ± 56.9	80 ± 5	---

a All data variances computed at the 99 % Student t level.

b Percent of thermogram exothermic acceleratory phase fitting linear portion of the autocatalytic rate plot at a 0.999 least squares value (R²).

Activation energies, computed at a 95% Excel[®] standard error level, reveal a 170.0 ± 27.7 kJ/mol energy of activation (R² = 0.9922) for the DNNC induction period using the five lower temperatures from 174 to 190 °C (Figure 4). At higher temperatures, the induction period time is short enough that it approaches the instrumental temperature equilibration regime, and accurate measurement becomes difficult. Little time is left for a linear induction period portion in the thermogram curve to develop, and this can mask the point of curve deflection where the acceleratory phase is initiated. An induction period activation energy, which includes all six temperatures, equals 160.5 kJ/mol but gives a less desirable linear curve fit (R² = 0.9903); therefore, the higher 170.0 kJ/mol is selected as more valid.

The 170 kJ/mol graphic plot uses, as the shortest induction time, a 72.2 s value determined at 190 °C which is in the same time regime as that of the shortest DNNC-d₆ induction time value (73.6 s) at the higher 194 °C temperature.

Insert Figure 4

A noticeably lower 104.2 ± 3.9 kJ/mol energy of activation is found for the DNNC exothermic acceleratory phase. Using the rate constant values for all six temperatures, an excellent linear data fit results ($R^2 = 0.9993$) as seen in Figure 5. The significantly lower 65.8 kJ/mol energy of activation ($170.0 \text{ kJ/mol} - 104.2 \text{ kJ/mol}$) for the exothermic acceleratory phase follows the same trend as that seen for the solid state DNNC thermochemical decomposition process.⁴ This trend suggests the possible formation of a small amount of decomposition product from DNNC itself during the endothermic induction period, which, upon reaching a threshold concentration, catalyzes initiation of the autocatalytic exothermic acceleratory phase where DNNC releases its stored energy. This lower energy of activation and autocatalytic decomposition process for the exothermic acceleratory phase of liquid state DNNC fits with catalytic behavior. It also mirrors the same pattern as that seen for the solid state DNNC decomposition process,⁴ as well as that reported for the neat liquid TNT catalyzed decomposition process.^{4,11}

Insert Figure 5

Because significantly slower kinetics result with DNNC-d₆, induction times are longer at corresponding temperatures used with DNNC; so, all six temperatures are included to obtain the 179.2 ± 14.3 kJ/mol ($R^2 = 0.9967$) induction period activation energy (Figure 4). The same activation energy trend was determined for the neat liquid state DNNC-d₆ thermochemical decomposition process (Table 3). The DNNC-d₆ rate constants at corresponding temperatures are significantly lower than those for DNNC and reflect the presence of a positive kinetic deuterium isotope effect (KDIE). As with the DNNC thermochemical decomposition process, a large portion of the DNNC-d₆ exothermic acceleratory phase provides an excellent $R^2 = 0.999$ linear fit with the autocatalytic rate plot. A

noticeably lower 104.5 ± 10.4 kJ/mol activation energy ($R^2 = 0.9949$) also was observed for the DNNC-d₆ acceleratory phase compared to its induction period (Figure 5). For both DNNC and DNNC-d₆, the higher induction period activation energy is statistically significant even at a most strenuous 99% variance level (Table 3).

Activation energy (E_{act}) comparisons for solid and liquid state DNNC thermochemical decomposition also are shown in Table 3. While DNNC is considered to be a thermally stable compound, given enough time and energy, solid state DNNC proceeds through a slow thermochemical decomposition process; and, like its liquid phase decomposition process, proceeds with an induction period activation energy that is higher than that seen for the acceleratory phase.

Table 3.^a Activation Energy (kJ/mol) Comparisons between Liquid and Solid State DNNC Thermochemical Decomposition Processes.

thermogram portion	liq. DNNC (R^2)	liq. DNNC-d ₆ (R^2)	sol. DNNC (R^2)	sol. DNNC-d ₆ (R^2)
induction period	170.0 ± 50.8 (0.992)	179.2 ± 23.7 (0.997)	128.1 (0.992) ⁴	not determined
acceleratory phase	104.2 ± 6.5 (0.999)	104.5 ± 17.2 (0.995)	105.6 (calc.) ⁴	115.2 (0.998) ⁴

^a Variances computed at Excel[®] 99% standard error level

Molecular Kinetic Deuterium Isotope Effect. The molecular KDIE for a given compound is determined by comparing thermochemical decomposition rates of the un-labeled molecule (DNNC) with the perdeuterio-labeled molecule (DNNC-d₆). Comparing both induction period and acceleratory phase data at the same temperatures in Tables 1 and 2, shows that the non-isotopically labeled (normal) DNNC thermochemically decomposes more rapidly than its fully deuterium-labeled DNNC-d₆ analogue. Like that previously reported for liquid TNT,¹¹ solid TATB,⁵ solid and liquid HMX,^{9,13} solid and liquid RDX,^{12,13} and solid DNNC,⁴ a positive molecular kinetic deuterium isotope effect (KDIE) defines the liquid state DNNC thermochemical decomposition process.

Insert Figure 6

This positive KDIE clearly is observed in Figure 6 where individual DNNC and DNNC-d₆ thermograms taken at 174 °C are compared. Figure 7 displays how the magnitude of the KDIE can reveal the specific rate-controlling homolytic bond cleavage associated with the DNNC molecule. Table 4 lists the KDIE values obtained at each temperature using the DNNC and DNNC-d₆ induction periods and the overall KDIE determined for the entire 172 to 194 °C temperature range. The induction period KDIE is determined by dividing the DNNC-d₆ induction time with the DNNC induction time (t_{id}/t_{ih}).^{10,11} A molecular KDIE value of 1.76 found during the induction period reflects a primary effect and identifies C-H bond rupture in the ring methylene (-CH₂-) groups of the DNNC molecule, or a structural fragment derived from it, as being the rate-controlling mechanistic feature (Figure 7).

Insert Figure 7

Table 4.^a Induction Period Kinetic Deuterium Isotope Effect (KDIE) for DNNC.

temperature (°C)	DNNC-d ₆ induction period (min)	DNNC induction period (min)	KDIE value (no units)
194	1.23 ± 0.53	0.88 ± 0.17	1.40 ± 0.47
190	2.11 ± 0.41	1.20 ± 0.29	1.76 ± 0.32
186	2.83 ± 0.59	1.56 ± 0.41	1.81 ± 0.34
182	4.57 ± 0.89	2.47 ± 0.10	1.85 ± 0.20
178	7.29 ± 1.79	3.81 ± 1.13	1.91 ± 0.38
172	10.87 ± 1.21	5.99 ± 2.29	1.85 ± 0.30
average	-----	-----	1.76 ± 0.33

^a Data variances computed at the 99% Student t level

Immediately following the endothermic induction period, the DNNC thermochemical decomposition process enters into an exothermic autocatalytic acceleratory phase. In this portion of the thermogram (Table 5), KDIE behavior is determined by dividing the normal DNNC rate constant by the deuterium-labeled DNNC-d₆ rate constant (k_h/k_d).¹¹ Within the 174 to 194 °C temperature range, a substantial overall molecular KDIE equal to 1.65 is found (Table 5). Among the myriad of chemical reaction channels in play during this complex exothermic acceleratory portion of the thermochemical decomposition process, a rate-controlling C-H bond rupture occurs in the substantially slowest one. This C-H bond rupture is derived from the methylene sites of the cyclic DNNC molecule, or a structural fragment derived from it, and significantly controls the overall exothermic energy release rate. This 1.65 KDIE value is calculated to be 3.17 when mathematically normalized to room temperature conditions (298 K)³⁸ and further verifies assignment of a rate-controlling C-H bond rupture where, at 298 K, a primary KDIE equal to 2.5 is considered to be the minimum.³⁹ This primary 1.65 KDIE value for the exothermic acceleratory phase decomposition of liquid DNNC is quite similar to that found for the liquid

Table 5.^a Acceleratory Phase Kinetic Deuterium Isotope Effect (KDIE) for DNNC

temperatur e (°C)	DNNC rate constant ($k \times 10^{-3} \text{ s}^{-1}$)	DNNC-d ₆ rate constant ($k \times 10^{-3} \text{ s}^{-1}$)	KDIE expl. value	KDIE at 25 °C ³⁸
194	12.15 ± 0.48	7.16 ± 0.89	1.70 ± 0.13	3.36
190	9.61 ± 0.43	5.94 ± 0.45	1.62 ± 0.09	3.16
186	7.55 ± 0.64	4.71 ± 0.35	1.60 ± 0.11	3.10
182	5.87 ± 0.39	3.58 ± 0.19	1.64 ± 0.08	3.14
178	4.58 ± 0.25	2.76 ± 0.29	1.66 ± 0.12	3.14
174	3.45 ± 0.16	2.06 ± 0.10	1.67 ± 0.07	3.12
average	-----	-----	1.65 ± 0.09	3.17

^a All data variances computed at the 99% Student t level

decomposition process of structurally-related RDX which was measured using three different analysis methods (Table 6). Rounded off to the nearest tenth decimal place, a 1.6 KDIE value emerges for the exothermic portion of both the liquid state DNNC and RDX thermochemical decomposition processes.

Table 6. Comparative KDIE Values for Exothermic Liquid State DNNC and RDX Thermochemical Decomposition Process

temp. range (°C)	reference	compound	analysis method	KDIE value
174 - 194	this work	DNNC/DNNC-d ₆	isothermal DSC	1.65
227 - 242	12	RDX/RDX-d ₆	isothermal DSC	1.64
212 only	12	RDX/RDX-d ₆	isothermal QUVA ^a	1.57
206 - 216	13	RDX/RDX-d ₆	isothermal TGA	1.56

^a Quenched Ultra-Violet Absorbance measurement

For comparison, molecular KDIE-based IDSC analyses of the solid state DNNC thermochemical decomposition process also reveal a primary 1.47 KDIE and a rate-controlling C-H bond rupture for the exothermic acceleratory portion of the decomposition process. In contrast to the liquid DNNC decomposition results, however, the solid state DNNC induction period affords a secondary 1.22 KDIE value suggesting that homolytic ring C-N ring bond cleavage likely constitutes the endothermic rate-controlling feature prior to transitioning into the exothermic acceleratory phase.⁴

The homolytic rate-controlling chemical bond rupture, and resultant atom transfer during the decomposition process of an energetic compound, depends upon its chemical structure and resultant chemical environment.²³ As seen in Figure 8, the TNT molecule possesses a chemical structure where two types of C-H bonds reside in vastly different chemical environments. This is reflected by the large

proton NMR shifts between the C-H bonds of the saturated aliphatic pendant methyl (-CH₃) group and the aromatic phenyl C-H bonds (Δ = 6.32 ppm). TNT forms mainly condensed phase products during thermochemical decomposition^{40,41} via a rate-controlling C-H bond rupture at the pendant methyl group site;¹¹ and the aromatic C-H bonds remain intact when forming these condensed phase decomposition products.^{10,11,40,41} The chemical structure of the DNNC, where all C-H bonds are embodied in saturated aliphatic ring methylene groups, represents a far different structural environment from TNT (Figure 8).

Insert Figure 8

The rate-controlling C-H bond rupture found in the exothermic liquid state DNNC thermochemical decomposition process only can emanate from the saturated methylene groups in the DNNC ring structure (Figure 1); but, the differences in their chemical environment are much more subtle than with TNT. This subtle difference in DNNC molecular structure, and resultant chemical environment, is illustrated by the very small NMR proton shift between the two C-2 methylene protons versus the four C-4/C-6 methylene protons (Δ = 0.83 ppm) seen in Figure 8. While the two methylene groups at the C-4 and C-6 DNNC ring positions are chemically and structurally equivalent, the methylene at the C-2 position is neither chemically nor structurally equivalent with the C-4 and C-6 methylenes. This subtle difference in the DNNC chemical structure raises two questions. Are all three methylene groups in the DNNC ring structure the source for this rate-controlling C-H bond rupture for the DNNC thermochemical decomposition process, like that found in RDX with its three equivalent methylenes? Or, secondly, is the structural and resultant chemical non-equivalence of the DNNC ring structure sufficiently different to restrict this C-H bond rupture to either the equivalent C-4/C-6 methylene sites, or alternatively, to the non-equivalent nitrogen sandwiched C-2 site? An investigative mechanistic IDSC comparison of the four DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆ isotopomers enters into the DNNC molecule and differentiates between these chemically similar DNNC ring methylenes. In doing so, it determines the structural site from which C-H bond rupture ultimately regulates the DNNC thermochemical decomposition process. A similar approach was used for the nitroraromatic compound,

HNS (hexanitrostilbene), to analyze the more chemically diverse aromatic and vinyl C-H bonds contained in its molecular structure, but no primary KDIE or resultant rate-controlling C-H bond rupture was found.⁴²

Structural Kinetic Deuterium Isotope Effect. A structural KDIE represents an approach which compares different internal structural features of a given compound by using both the unlabeled compound (DNNC) and the perdeuterio-labeled compound (DNNC-d₆), as bracketed baseline data, against analogous, partially labeled isotopomers (DNNC-d₂, DNNC-d₄). There is a 9.6 kJ/mole energy difference between the C-H bond ground state vibrational energy and that of the analogous but stronger C-D bond. If bond energy differences between the non-equivalent C-2 methylene and the equivalent C-4/C-6 methylene positions in the unsymmetrical DNNC molecule are greater than 9.6 kJ/mole, selectively deuterium-labeled DNNC-d₂ and DNNC-d₄ isotopomers could reveal which methylene position provides the rate-controlling C-H bond rupture for the DNNC decomposition process. Consistent with the KDIE concept, if the DNNC-d₂ and DNNC-d₄ isotopomers seen in Figure 9 were synthesized and subjected to IDSC analyses, the methylene position providing the rate-controlling C-H bond rupture could be identified. Should the C-2 methylene position exclusively provide this rate-controlling C-H bond rupture, then the partially labeled DNNC-d₂ isotopic isomer would give the same slower rate constant (k_{d2}) as DNNC-d₆ (k_{d6}), and the partially deuterium labeled DNNC-d₄ would give the same rate constant (k_{d4}) as DNNC (k). Conversely, if the chemically equivalent C-4/C-6 methylenes are the source of the C-H rate-controlling bond cleavage, DNNC-d₂ would have the same rate constant (k_{d2}) as DNNC (k), and DNNC-d₄ (k_{d4}) should give the same rate constant as does the slower one exhibited by DNNC-d₆ (k_{d6}).

Insert Figure 9

The partially labeled isotopic isomers, DNNC-d₂ and DNNC-d₄, were synthesized (Experimental Section) where discreet perdeuterio -CD₂- methylene groups are introduced into the DNNC molecular structure. To the nearest whole number, proton NMR integration verified that each contained the

intended two and four deuterium atoms, respectively. However, for **both** the synthesized DNNC-d₂ and DNNC-d₄ compounds, proton NMR integration for the specific C-2 and C4/C-6 methylenes showed a 1:2 integration ratio indicating that random –CD₂- methylene scrambling into all three DNNC ring positions resulted with both isotopomers. Under the alkaline reaction conditions, it was found that all three C-2, C-4, and C-6 positions in the DNNC ring structure are subject to a formylation/deformylation equilibrium involving intermixing formaldehyde molecules which are generated from the ADIOL reactant and available from the additional formaldehyde reactant. Unfortunately, this equilibrium exchange occurred faster than did ring self-assembly (Figure 10).

Insert Figure 10

Mass spectral analysis of the synthesized DNNC-d₂ and DNNC-d₄ samples revealed that each contained a mixture of all four isotopomers, DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆, in percentages that mirrored the intended pure, selectively-positioned isotopic isomers DNNC-d₂ and DNNC-d₄ seen in Figure 9. The DNNC-d₂ isotopomer predominated in the mixed, synthesized DNNC-d₂ sample, and the DNNC-d₄ isotopomer was predominant in the mixed, synthesized DNNC-d₄ sample. The net result of this random –CD₂- methylene ring incorporation, and the resultant percent mixtures of all four isotopic isomers in the synthesized DNNC-d₂ and DNNC-d₄ samples, produced bulk materials where the DNNC-d₂ behaved as if it were one-third deuterium atom labeled at each methylene (C-2, C-4, & C-6) ring position, and the DNNC-d₄ bulk material behaved as if it were two-thirds deuterium labeled at each methylene position (Figure 11). This serendipitous result necessitated using a modified and slightly more complex approach to determine whether or not a specific methylene group in the DNNC chemical structure is responsible for the rate-controlling C-H bond rupture.

Insert Figure 11

This modified approach invokes two reasonable assumptions. First, when possible, the homolytic, covalent C-H bond rupture, and H atom transfer, will always occur in preference to that of the stronger C-D covalent bond. Secondly, should the rate-controlling step involve and be forced to proceed at one

specific DNNC methylene site, and this methylene site is deuterium labeled, then C-D bond rupture will occur with a concomitant decrease in the decomposition rate and associated rate constant.

Figure 11 represents a valid model with which to evaluate kinetics data obtained with DNNC and its three deuterium-labeled isotopomers, DNNC-d₂, DNNC-d₄, and DNNC-d₆. Figure 11 (top) displays three -CD₂- randomly labeled DNNC-d₂ molecules, which combined, mirror the synthesized DNNC-d₂ isotopic isomer that behaves as if it were one-third deuterium labeled at each methylene position. If the rate-controlling C-H bond rupture emanates from the C-2 methylene site, slower C-D bond cleavage would occur only one out of three times, and C-H bond rupture would occur twice as often. Thus, DNNC-d₂ should give a one third (33%) rate constant reduction between the faster unlabeled DNNC rate constant and the relative 100% rate constant reduction of DNNC-d₆. Alternatively, if the equivalent C-4/C-6 methylene positions are the source for the rate-controlling C-H bond rupture, a slower C-D bond rupture, and concomitant rate constant reduction would not occur with the DNNC-d₂ isotopic isomer because a preferred C-H bond rupture is always available. Figure 11 (bottom) displays three -CD₂- randomly labeled DNNC-d₄ molecules, which combined, mirror the synthesized DNNC-d₄ isotopic isomer that behaves as if it were two-thirds deuterium labeled at each methylene position. With the synthesized DNNC-d₄ isotopic isomer, a C-H rate-controlling bond rupture relegated to the C-2 methylene would effect a two-thirds (67%) rate constant reduction since this methylene site is deuterated two out of three times. If the rate-controlling step were provided by the C-4/C-6 sites, DNNC-d₄ would give a one third (33%) rate constant reduction. This is summarized in Table 7.

Table 7. Expected Rate Constant Reduction of Methylene Sites Relative to DNNC/DNNC-d₆ Rate Constant Difference

isotopomer compound	RCS at C-2 rate constant reduction	RCS at C-4/C-6 rate constant reduction
DNNC-d ₂	33%	0%

DNNC-d ₄	67%	33%
DNNC-d ₆	100%	100%

RCS = rate-controlling step (C-H bond rupture)

The DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆ thermochemical decomposition processes were analyzed by IDSC at 186 °C, and a systematic rate reduction was observed. Figure 12 shows an individual IDSC run for each isotopic isomer where the decomposition rate progressively slows in the order: (fastest) DNNC > DNNC-d₂ > DNNC-d₄ > DNNC-d₆ (slowest). The fact that, **both** the DNNC-d₂ and DNNC-d₄ rate constants are reduced significantly (Table 8) during the exothermic acceleratory phase, immediately identifies the C-2 methylene position as being the structural site for the rate-controlling C-H bond rupture for this portion of the thermochemical decomposition process.

Insert Figure 12

Careful rate constant data analysis of the experimental structural KDIE data in Table 8 shows that, within the total rate difference between DNNC and fully deuterium-labeled DNNC-d₆, DNNC-d₂ decomposes about one-third (31%) more slowly than DNNC, and DNNC-d₄ nearly two-thirds (60%) more slowly (Table 8). That is, the structural KDIE rate reduction percent for DNNC-d₂ equals $[k_{\text{DNNC}} - k_{\text{DNNC-d}_2}] \text{ divided by } k_{\text{DNNC}} - k_{\text{DNNC-d}_6}] \text{ times } 100$, and the structural KDIE rate reduction percent for DNNC-d₄ equals $[k_{\text{DNNC}} - k_{\text{DNNC-d}_4}] \text{ divided by } k_{\text{DNNC}} - k_{\text{DNNC-d}_6}] \text{ times } 100$. This data very closely matches the calculated criteria expected if the non-equivalent C-2 methylene position in the DNNC molecule is the origin for the rate-controlling C-H bond rupture site, and further experimental data analysis strengthens this conclusion.

Table 8^a. IDSC Rate Constant Data Reduction for the DNNC and Its Deuterated Isotopomers

kinetic data	DNNC	DNNC-d ₂	DNNC-d ₄	DNNC-d ₆
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rate constant (k in s ⁻¹)	7.79 x 10 ⁻³ ± 0.25	6.84 x 10 ⁻³ ± 0.30	5.92 x 10 ⁻³ ± 0.57	4.68 x 10⁻³ ± 0.61
interval (s ⁻¹)		0.95 x 10 ⁻³	0.92 x 10 ⁻³	1.24 x 10⁻³
percent k reduction	0%	31%	60%	100%
Accel. phase linearity (%)	93	89	88	76
no. runs	6	5	5	5

^a All data variances computed at the 99% Student t level

Rate constant interval differences in Table 8 reveal nearly identical interval reductions between the DNNC and DNNC-d₂ rate constant values, and between the DNNC-d₂ and DNNC-d₄ rate constants; however, a much larger 1.24 X 10⁻³ s⁻¹ interval reduction appears between the DNNC-d₄ and DNNC-d₆ rate constants. Figure 13 displays this data in graph plot form and further suggests the experimental DNNC-d₆ rate constant, while quite reasonable, might actually be slightly lower than what is consistent with the other DNNC, DNNC-d₂, and DNNC-d₄ isotopomers. Plotting the number of hydrogen atoms (x-axis) in each DNNC isotopomer,⁴³ versus the measured rate constant (y-axis) in Figure 13, affords an excellent linear least squares fit ($R^2 = 0.994$), but Figure 13 also gives a linear y-intercept value for DNNC-d₆ (0 H-Atoms)⁴³ which suggests a rate constant equal to 4.77 x 10⁻³ s⁻¹, rather than the lower 4.68 x 10⁻³ s⁻¹, would be more reasonable.⁴⁴

Insert Figure 13

By graphing only the first three points corresponding to DNNC, DNNC-d₂, and DNNC-d₄ in an analogous plot (Figure 14), a near perfect linear least squares fit ($R^2 = 0.9999$ or 1.000) results and gives

Insert Figure 14

a y-intercept value at the DNNC-d₆ (0 H-atoms) isotopomer that defines a $4.98 \times 10^{-3} \text{ s}^{-1}$ revised rate constant value. When this revised rate constant ($4.98 \times 10^{-3} \text{ s}^{-1}$) is substituted for the $4.68 \times 10^{-3} \text{ s}^{-1}$ experimental data rate constant in Table 9, all three rate constant reduction interval differences match much more closely with the re-computed DNNC-d₄ to DNNC-d₆ interval falling between the two other intervals. Most importantly, a 34% rate constant reduction, versus calculated 33%, results for DNNC-d₂, and the expected 67% rate reduction surfaces for DNNC-d₄. Thus, the rate-controlling C-H bond rupture, which regulates the energy release rate of the exothermic acceleratory phase, originates at the non-equivalent C-2 methylene site sandwiched between the two DNNC ring nitrogen atoms.

Table 9. Revised DNNC-d₆ Rate Constant Data for DNNC and Its Deuterated Isotopomers

kinetic data	DNNC	DNNC-d ₂	DNNC-d ₄	DNNC-d ₆
rate constant (k in s ⁻¹)	7.79×10^{-3}	6.84×10^{-3}	5.92×10^{-3}	4.98×10^{-3}
interval (s ⁻¹)		0.95×10^{-3}	0.92×10^{-3}	0.94×10^{-3}
percent k reduction	0%	34%	67%	100%

Next, the induction period data is similarly evaluated to determine if this mechanistic feature also regulates this earlier portion of the DNNC thermochemical decomposition process. Induction period times also represent rate measurement data and have an inversely proportional relationship with corresponding reaction rate constants which cannot be directly measured by IDSC in this flat portion of the thermogram.¹¹ A fast endothermic reaction rate (large rate constant), occurring during the induction period, provides a short (small) induction time. Therefore, induction times should increase as the amount of deuterium labeled methylene groups increase in the DNNC isotopomer by the proportionate

percentages shown in parentheses: DNNC (0% baseline time) < DNNC-d₂ (33%) < DNNC-d₄ (67%) < DNNC-d₆ (100% maximum time).

Table 10 lists the averaged induction time (t_i) obtained at 186 °C for DNNC and each of its three deuterium labeled isotopomers. The increased induction times for both DNNC-d₂ and DNNC-d₄, compared to DNNC (Figure 15), again suggests that the rate-controlling C-H bond rupture emanates from the C-2 methylene site of the DNNC ring structure. Should this rate-controlling mechanistic feature be generated from the equivalent C-4 and C-6 methylenes, no induction time decrease for the DNNC-d₂ isotopomer, compared to DNNC, should result (Figure 11). Induction time interval differences between DNNC/DNNC-d₂, DNNC-d₂/DNNC-d₄, and DNNC-d₄/DNNC-d₆ do not follow the expected regular magnitude increase which should give a 33% induction time increase for DNNC-d₂ and a 67% increase for DNNC-d₄. Rather, induction time increases are 29 % for DNNC-d₂ and 46% for DNNC-d₄ using the initial experimental interval data obtained (Table 10).

Table 10.^a Induction Time Data for DNNC and Its Partially Deuterated Isotopomers at 186 °C

induction period data	DNNC	interval	DNNC-d ₂	interval	DNNC-d ₄	interval	DNNC-d ₆
no. IDSC runs	6		5		5		5
ave. induction time (s)	91.8 ± 23.0		115.7 ± 13.8		129.2 ± 25.1		173.9 ± 34.1
interval (s)		23.9		13.5		44.7	
percent reduction	0%		29%		46%		100%

^a All data variances computed at the 99 percent Student t level

Again, like the exothermic acceleratory phase data, an extended treatment of the induction time data clearly reflects the expected trend. A graphic trend line plot of experimental induction times versus the number of hydrogen atoms in DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆ (Table 10), only gives an $R^2 = 0.946$ linear least squares fit (Figure 15); but, comparison of a polynomial curved trend line and close examination of the linear trend line and interval differences from Table 10, suggest the induction time for DNNC-d₄ may be low compared to the other three isotopomers.

Insert Figure 15

In contrast to Figure 15, Figure 16 plots a least squares trend line fit for the induction times of DNNC, DNNC-d₂, and DNNC-d₆ only, where the DNNC-d₄ 129.2 s induction time data is excluded, and affords an excellent $R^2 = 0.998$ linear fit with a 13.81 slope value. A similar plot that includes the DNNC, DNNC-d₂, and DNNC-d₄ induction times, but excludes the DNNC-d₆ 173.9 s induction time (Figure 17), gives a much lower $R^2 = 0.976$ fit, and verifies that the abnormally low induction time comes from DNNC-d₄ rather than DNNC-d₆.

Insert Figures 16 & 17

Averaging the sum of the three induction time interval values found in Table 10, an interval of 27.4 s results over the entire DNNC to DNNC-d₆ isotopomer range. Substituting this averaged 27.4 s interval difference for the questionable 13.5 second interval difference between DNNC-d₂ and DNNC-d₄, and adding the 27.4 s to the 115.7 s induction time of DNNC-d₂, a 143.1 s induction time for DNNC-d₄ results which nearly matches the upper 99% Student t variance for this questionable 129.2 s induction period value. The calculated 27.4 s induction time interval, and resultant calculated 143.1 s induction time for DNNC-d₄, along with a revised 30.8 s interval difference in place of 44.7 s between DNNC-d₄ and DNNC-d₆ to maintain a 173.9 s induction time for DNNC-d₆, are substituted for the corresponding data in Table 10 to give Table 11. Using the revised data from Table 11, the DNNC-d₂ induction time increase remains at 29% for DNNC-d₂, but becomes a much more reasonable 62% for DNNC-d₄. The 29% DNNC-d₂ induction time increase is reasonably close to the expected 33% value, and the corrected

62% induction time increase for DNNC-d₄ (Table 11), versus 46% from Table 10, compares more favorably with the calculated 67% induction time increase expected.

Table 11. Revised Induction Time Data for DNNC and Its Partially Deuterated Isotopic Isomers

induction period data	DNNC	interval	DNNC-d ₂	interval	DNNC-d ₄	interval	DNNC-d ₆
no. IDSC Runs	6		5		5		5
Ave. induction time (sec)	91.8		115.7		143.1		173.9
interval (sec)		23.9		27.4		30.8	
percent reduction	0%		29%		62%		100%

A graphic plot of the revised induction time data in Table 11 for DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆ generates a linear trend line with a nearly identical linear $R^2 = 0.997$ fit and 13.68 slope (Figure 18) as that seen with the linear $R^2 = 0.998$ value and 13.81 slope found in Figure 16 where the suspect DNNC-d₄ induction time is excluded. Allowing that visually interpreted induction time data measurements are not as exact as acceleratory phase rate constants, this induction time data treatment further confirms that C-H bond rupture at the DNNC structural C-2 methylene position also controls the endothermic induction period portion of the liquid state DNNC thermochemical decomposition process.

Insert Figure 18

Conclusions

Liquid state thermochemical decomposition of DNNC, conducted between 174 to 194 °C, is an autocatalytic process where homolytic covalent C-H bond rupture, and resultant hydrogen atom transfer, constitutes a key mechanistic feature that determines the endothermic initiation and subsequent exothermic propagating energy release rates. **Molecular KDIE** data, taken with un-labeled DNNC and perdeuterio-labeled DNNC-d₆, displays a primary KDIE value for both the endothermic induction period and subsequent autocatalytic exothermic acceleratory phase (Figure 19, top). The initial endothermic induction period likely generates a catalytic species via a rate-controlling homolytic C-H bond rupture (KDIE = 1.76), which upon reaching a threshold concentration, initiates an exothermic autocatalytic decomposition process. The exothermic decomposition process then follows a rate that also is controlled by a homolytic C-H bond rupture (KDIE = 1.65) coming from one of the methylene groups comprising the DNNC ring structure. A significantly higher energy of activation is required to initiate the DNNC endothermic induction period (170.0 kJ/mol) than what is needed for the corresponding exothermic acceleratory portion of the respective decomposition process (104.2 kJ/mol). The 65.8 kJ/mol energy difference, coupled with its autocatalytic rate behavior supports this catalytic mechanistic interpretation for the liquid state DNNC thermochemical decomposition process. This same mechanistic trend previously was reported for the solid state DNNC thermochemical decomposition process (Table 3).⁴

Insert Figure 19

Structural KDIE data, obtained from comparing DNNC and perdeuterio-labeled DNNC-d₆ with partially deuterium labeled isotopomers DNNC-d₂ and DNNC-d₄, enters into the DNNC molecular ring structure and reveals that the rate controlling C-H bond rupture originates at the methylene (-CH₂-) site at the C-2 position of the DNNC molecule which is sandwiched between the two ring nitrogen atoms, or originates from a structural fragment that is generated from this structural site (Figure 19, bottom). The chemically and structurally equivalent methylene groups at the C-4 and C-6 positions of the DNNC molecule reside in a chemical environment which is subtly different from the third C-2 methylene

group. The subtle energy difference of the chemical environments between the C-2 methylene site and the C-4/C-6 equivalent methylene sites, or the corresponding structural fragments that provide the rate-controlling C-H bond rupture, must exceed the 9.6 kJ/mol ground state vibrational energy difference between the C-H and C-D bond. If this were not the case, the rate-controlling C-H bond rupture, and hydrogen atom transfer, would occur randomly at all three DNNC methylene positions. The C-4/C-6 methylenes contribute little or no significant role in determining the overall liquid state DNNC thermochemical decomposition and energy release rates.

Apparently, the liquid state DNNC induction period requires a higher activation energy (170 kJ/mol) than does the solid state (128 kJ/mol)⁴ to initiate the subsequent exothermic portion of the thermochemical decomposition process. The liquid state (104 kJ/mol) and solid state (105 kJ/mol)⁴ DNNC exothermic acceleratory phases have a similar activation energy once energy release commences. While homolytic C-H bond rupture determines both the endothermic induction time duration and the exothermic acceleratory phase energy release rate in liquid state DNNC thermochemical decomposition, rate-controlling homolytic C-H bond dissociation only is found during the acceleratory phase of the solid state thermochemical decomposition process. Solid state DNNC endothermic induction period kinetics appear to be regulated by a different rate-controlling bond rupture as previously reported.⁴

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References and Notes

- (1) Portions of this material were presented at the following conferences: (a) Shackelford, S. A.; Goldman, J. F.; Menapace, J. A.; Hendrickson, S. A. *35th International Conference of ICT: Energetic Materials, Structure and Properties*; Karlsruhe, Germany, Jun 29-Jul 2, 2004; (b) Shackelford, S. A.; Goldman, J. F. *203rd Nat. Am. Chem. Soc. Mtg.*; San Francisco, CA, Apr 5-10, 1992; (c) Shackelford, S. A.; Goldman, J. F. *22nd International Conference of ICT: Combustion and Reaction Kinetics*; Karlsruhe, Germany, Jul 2-5, 1991.
- (2) Experimental IDSC thermochemical decomposition investigations were conducted at The F. J. Seiler Research Laboratory (FJSRL), USAF Academy, CO, USA prior to its Sep 30, 1995 decommissioning; (a) Directorate of Chemical Sciences, FJSRL, (b) Department of Chemistry, USAF Academy.
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- (43) To ensure the DNNC-d₆ isotopomer rate constant could be predicted by a y-intercept in graphic Figure 14, the x-axis had to reflect the number of H-atoms in each isotopomer; so, DNNC-d₆ is represented with 0 H-Atoms on the x-axis. Correspondingly, DNNC-d₄ is (2-H Atoms), DNNC-d₂ (4 H-Atoms), and DNNC (6 H-Atoms).
- (44) The y-intercept in Figure 13 is 0.00477 when carried out to three significant figures even though the Excel-based graph gives this value to only two significant figures (0.0048) as plotted.

Graphics/Figures

There are 19 figures submitted: one figure per page starting with manuscript page 33 and ending on manuscript page 51.

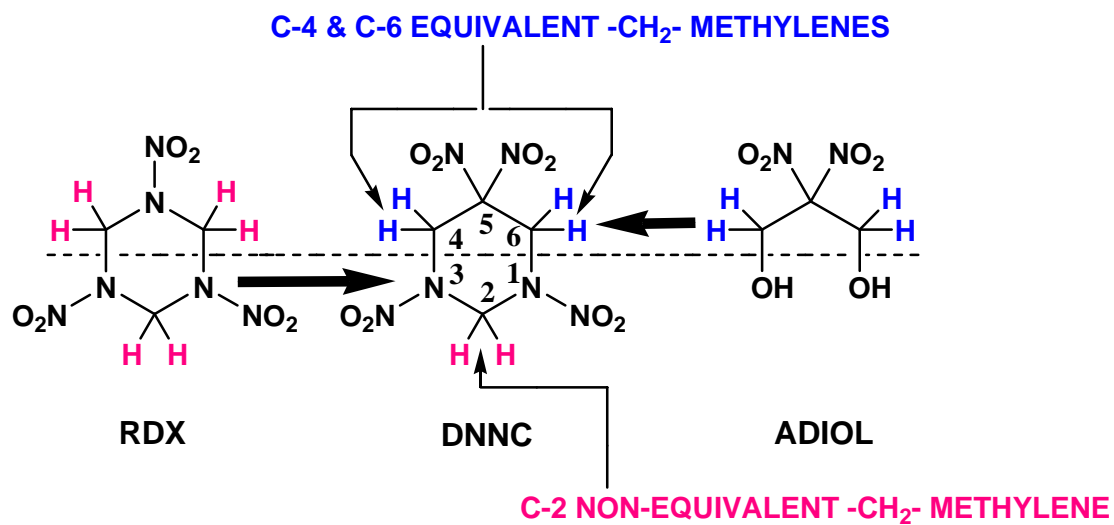


Figure 1

Figure 1. Unique hybrid chemical structure of the DNNC molecule.

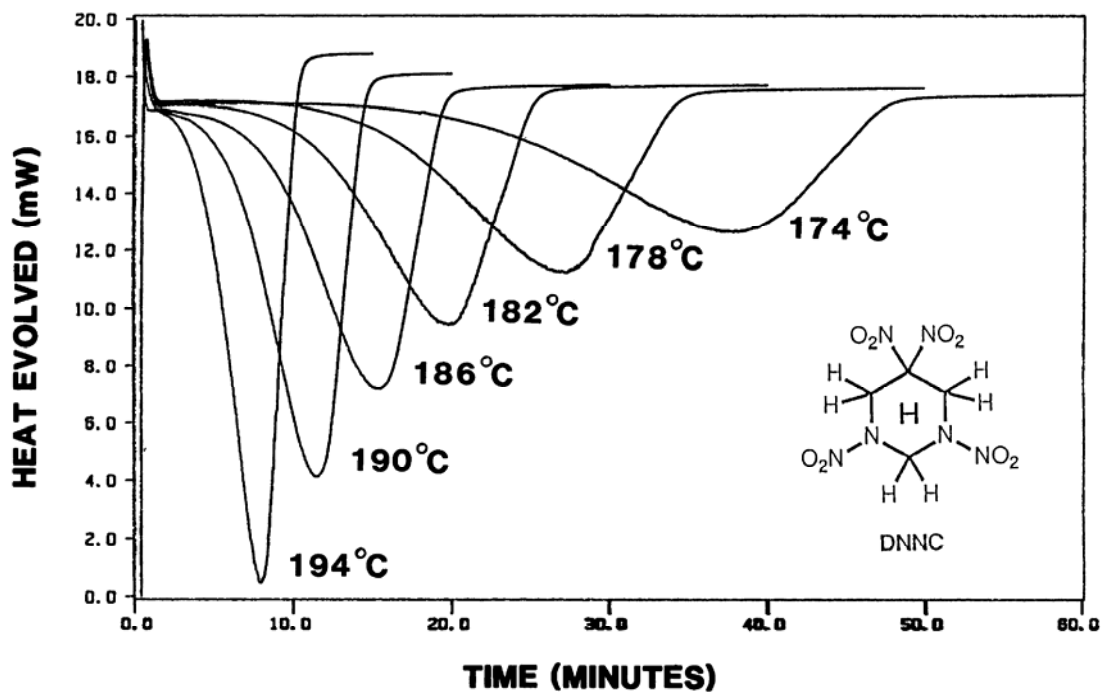


Figure 2. Individual IDSC thermograms of DNNC from 174 °C to 194 °C taken at 4 °C intervals.

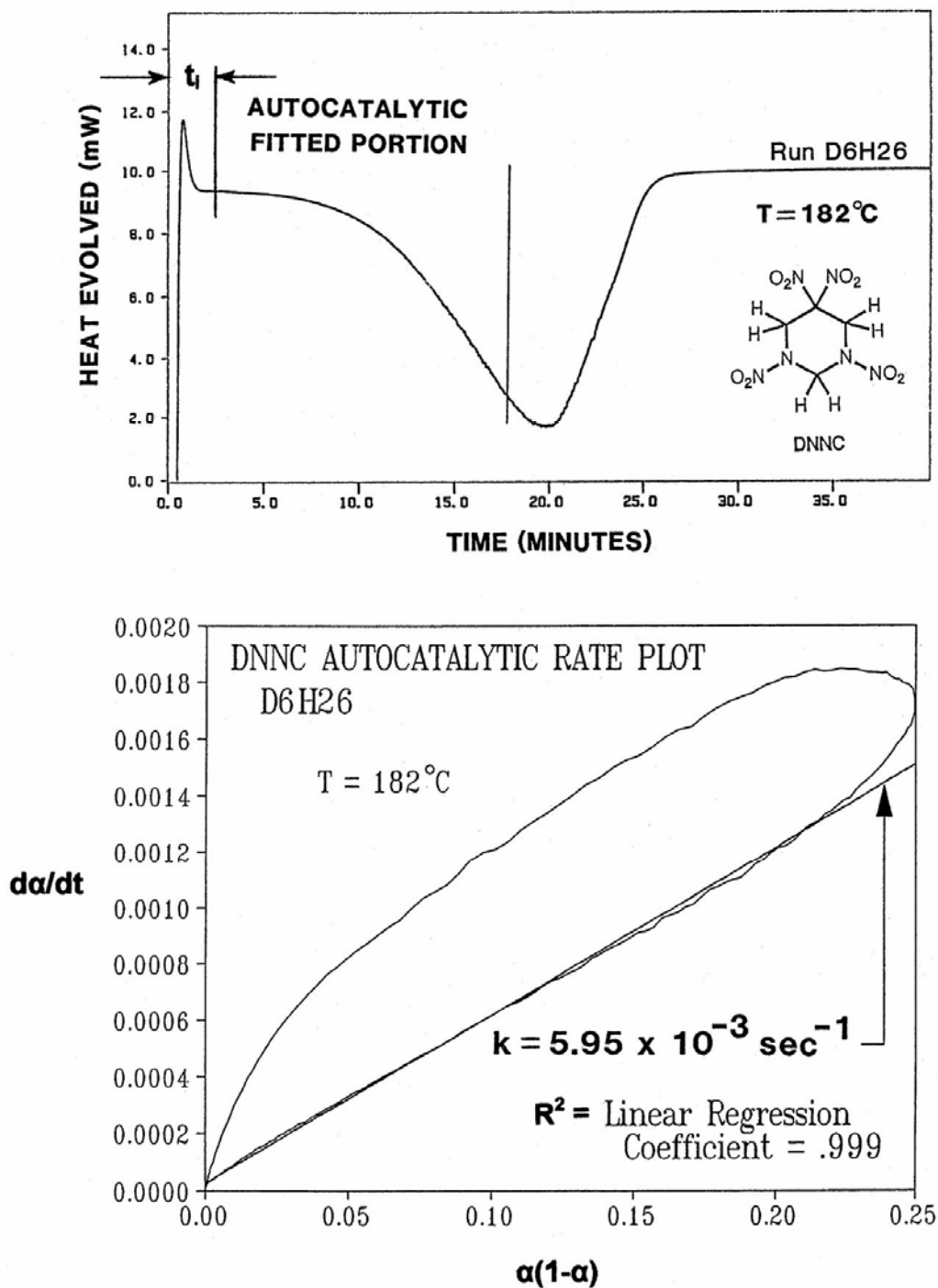


Figure 3. (top) DNNC isothermal DSC thermogram (Run D6H26) illustrating the portion of the exothermic acceleratory phase that fits autocatalytic kinetics following the endothermic induction period (t_i). **(bottom)** Corresponding autocatalytic rate plot for DNNC (Run D6H26) illustrating the linear kinetic fit of the exothermic acceleratory phase and slope-determined rate constant (k).

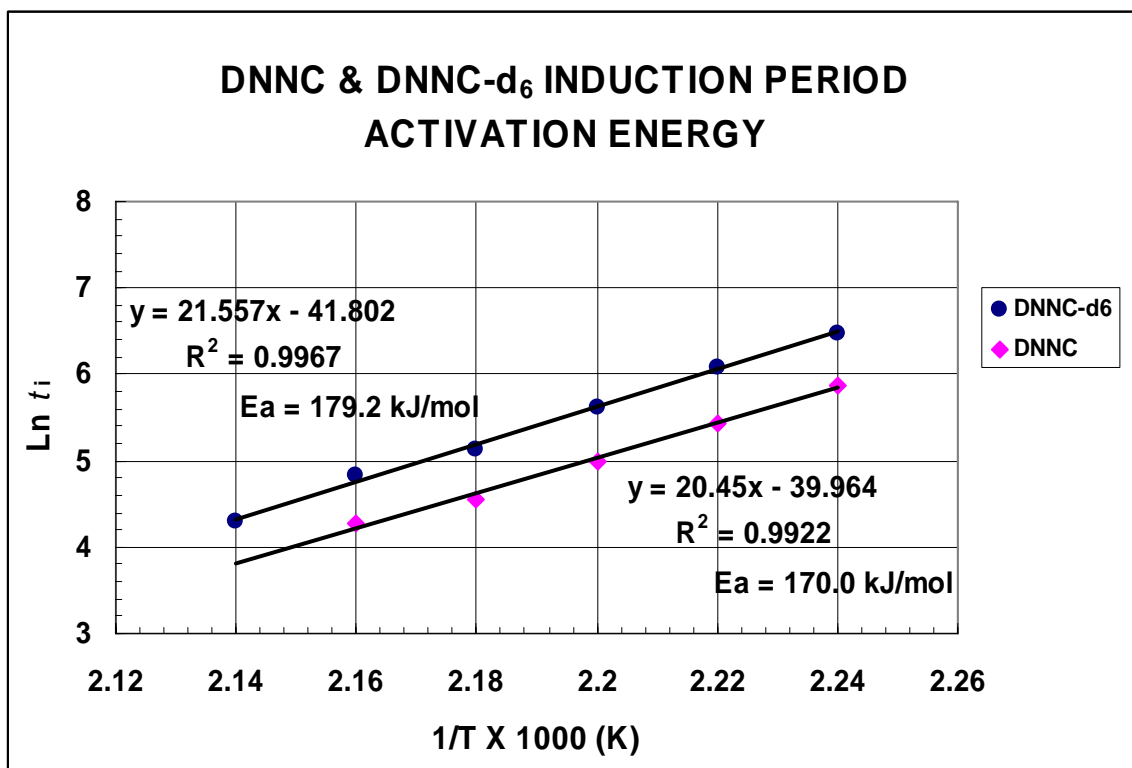


Figure 4. Kinetic data plot providing the activation energy for the DNNC endothermic induction period.

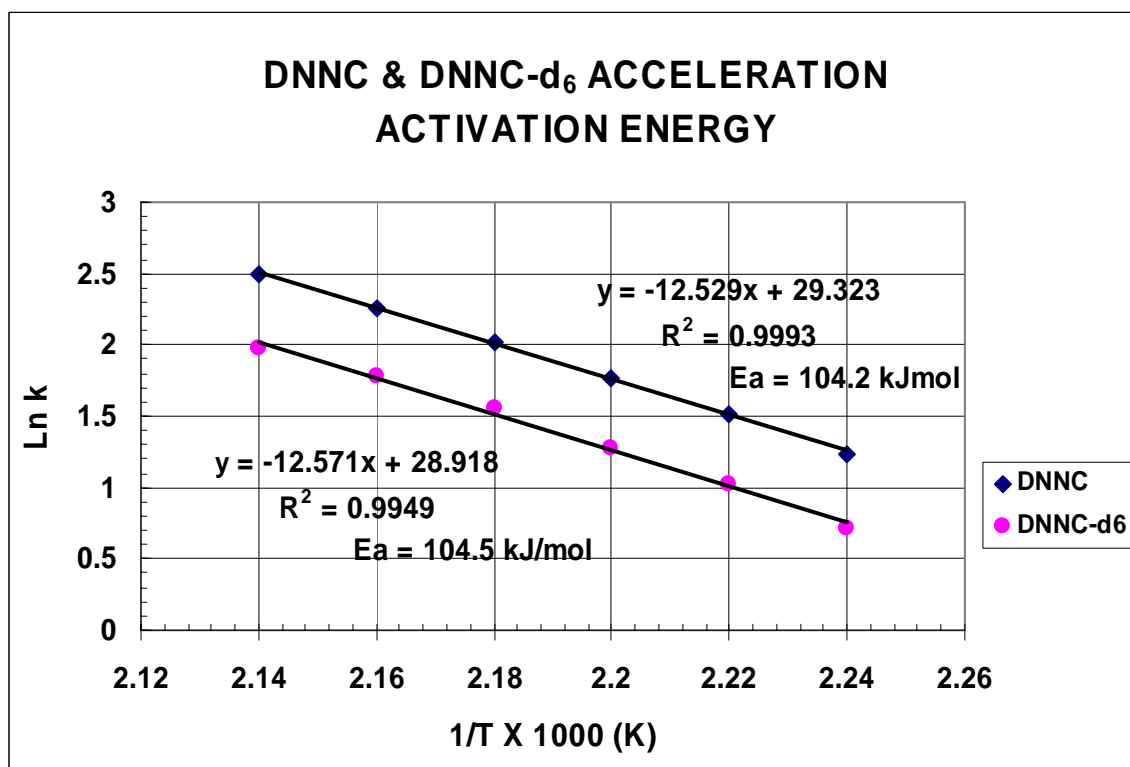


Figure 5. Kinetic data plot for activation energy of the DNNC & DNNC-d₆ exothermic acceleratory phase.

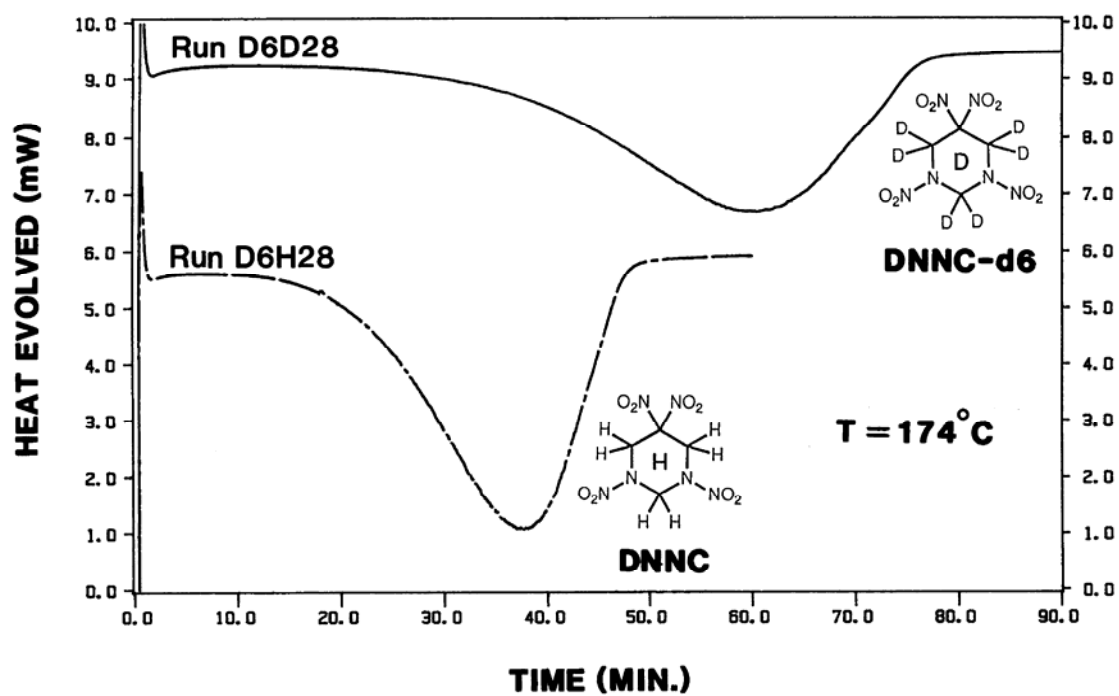


Figure 6. Individual DNNC and DNNC-d₆ IDSC thermograms compared at 174 °C.

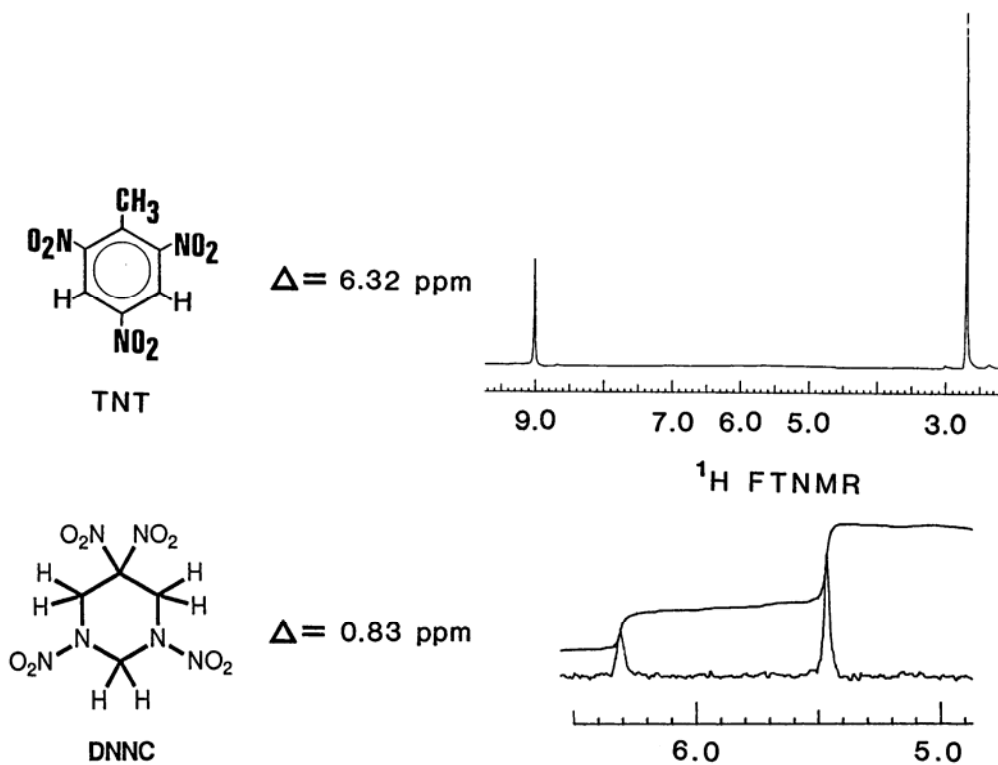
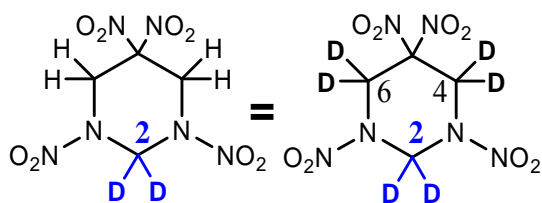


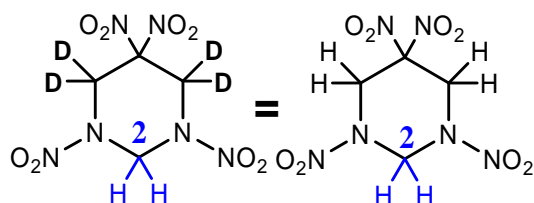
Figure 8. Comparative proton NMR chemical shift magnitudes of TNT C-H bonding ($\Delta = 6.32$ ppm) versus DNNC ring methylene C-H bonding ($\Delta = 0.83$ ppm).

If Non-Equivalent C-2 Position is Site of Rate-Controlling C-H Bond Rupture:



KDIE of DNNC-d₂ equals DNNC-d₆

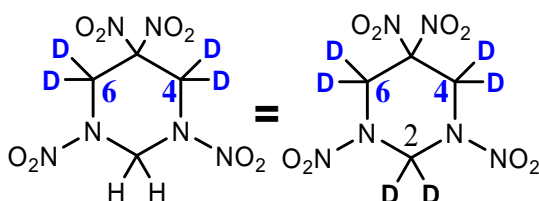
$$\frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_2}} = \frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_6}} \geq 1.41$$



No KDIE for DNNC-d₄

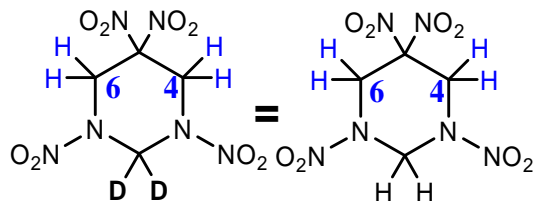
$$\frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_4}} = 1.00$$

If Equivalent C-4 or C-6 Positions are Site of Rate-Controlling C-H Bond Rupture



KDIE of DNNC-d₄ equals DNNC-d₆

$$\frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_4}} = \frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_6}} \geq 1.41$$



No KDIE for DNNC-d₂

$$\frac{k_{\text{DNNC}}}{k_{\text{DNNC-d}_2}} = 1.00$$

Figure 9. Theoretical KDIE results with specific partially deuterium-labeled DNNC-d₂ and DNNC-d₄ isotopomers.

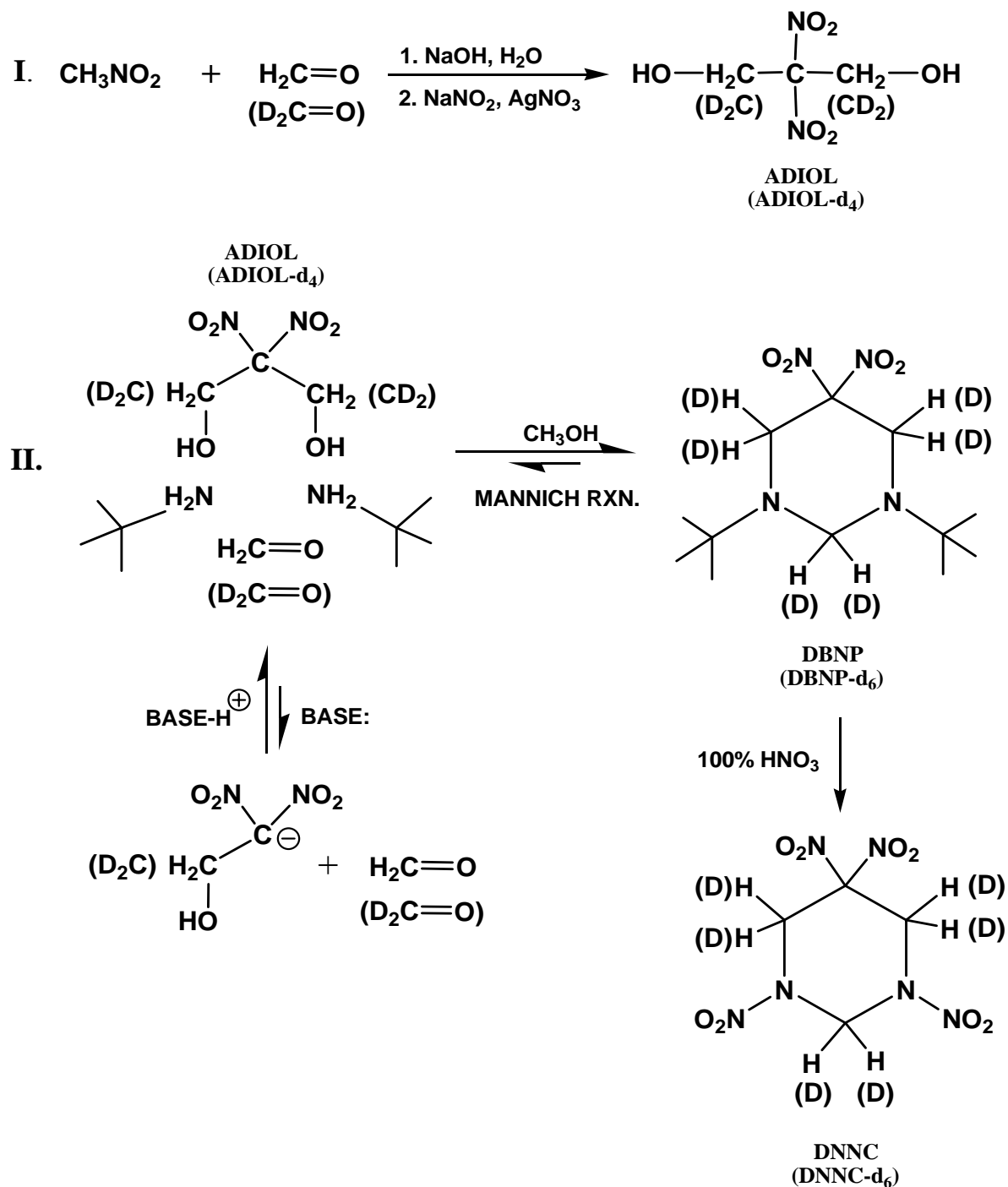


Figure 10. General synthesis scheme used for ADIOL, ADIOL- d_4 and the four DNNC isotopomers.

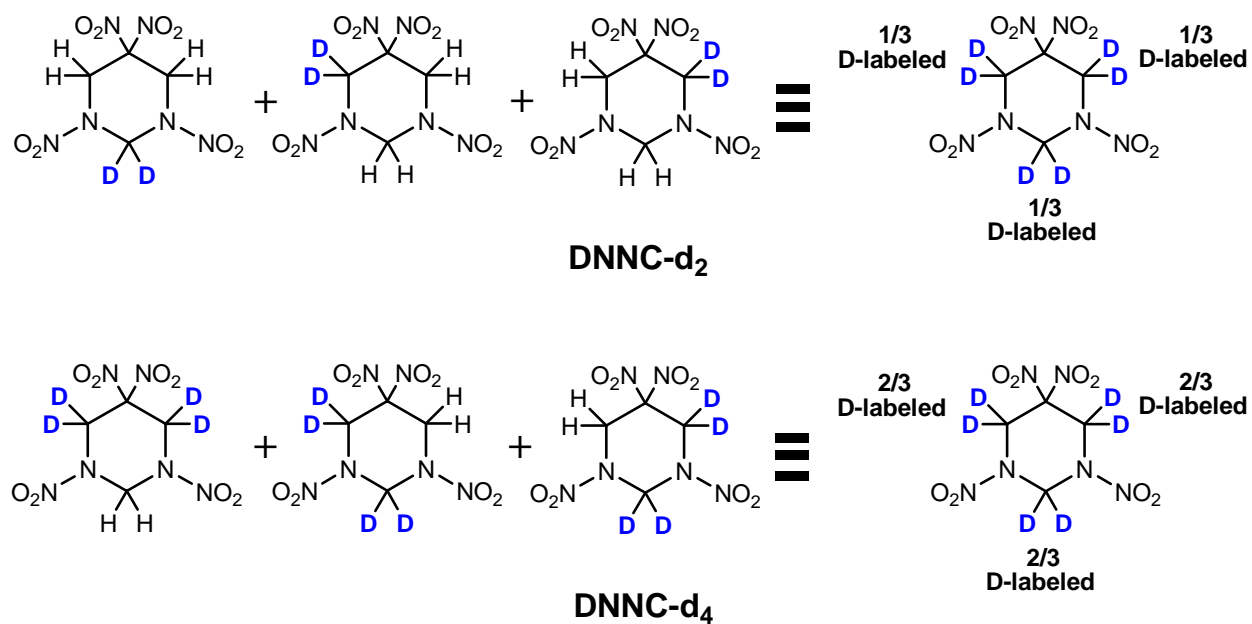


Figure 11. Overall kinetic behavior of random partially deuterium-labeled DNNC-d₂ and DNNC-d₄ isotopomer bulk samples.

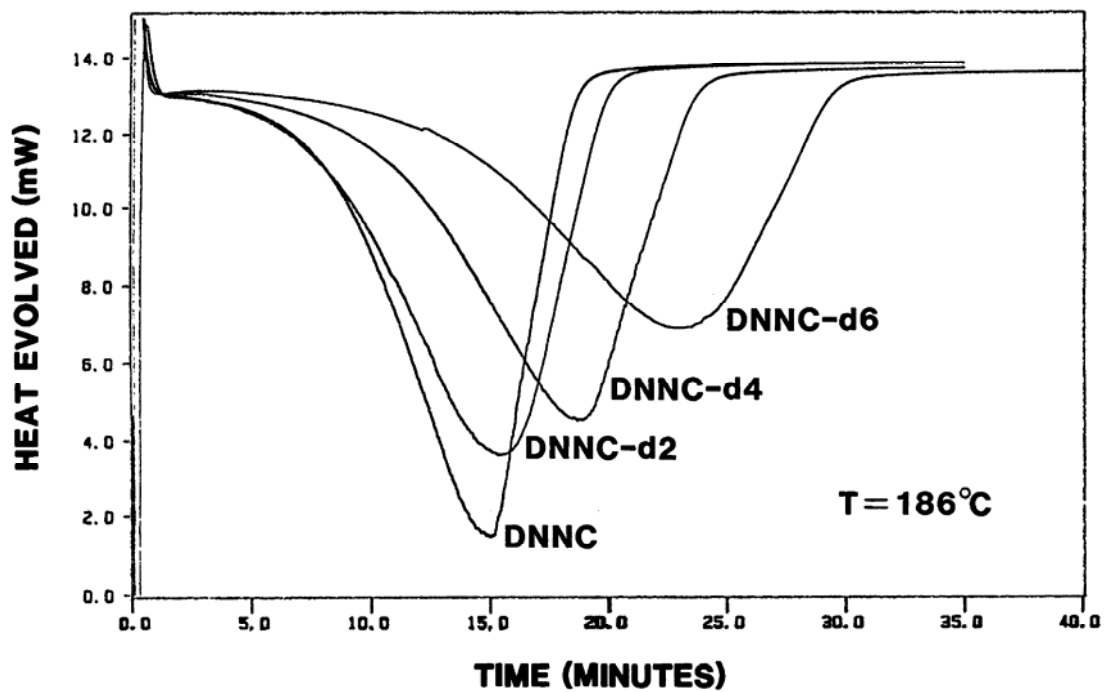


Figure 12. Comparison of individual DNNC, DNNC-d₂, DNNC-d₄, and DNNC-d₆ isotopomer thermograms at 186 °C.

RATE CHANGE VS. DNNC D-ATOM INCORPORATION

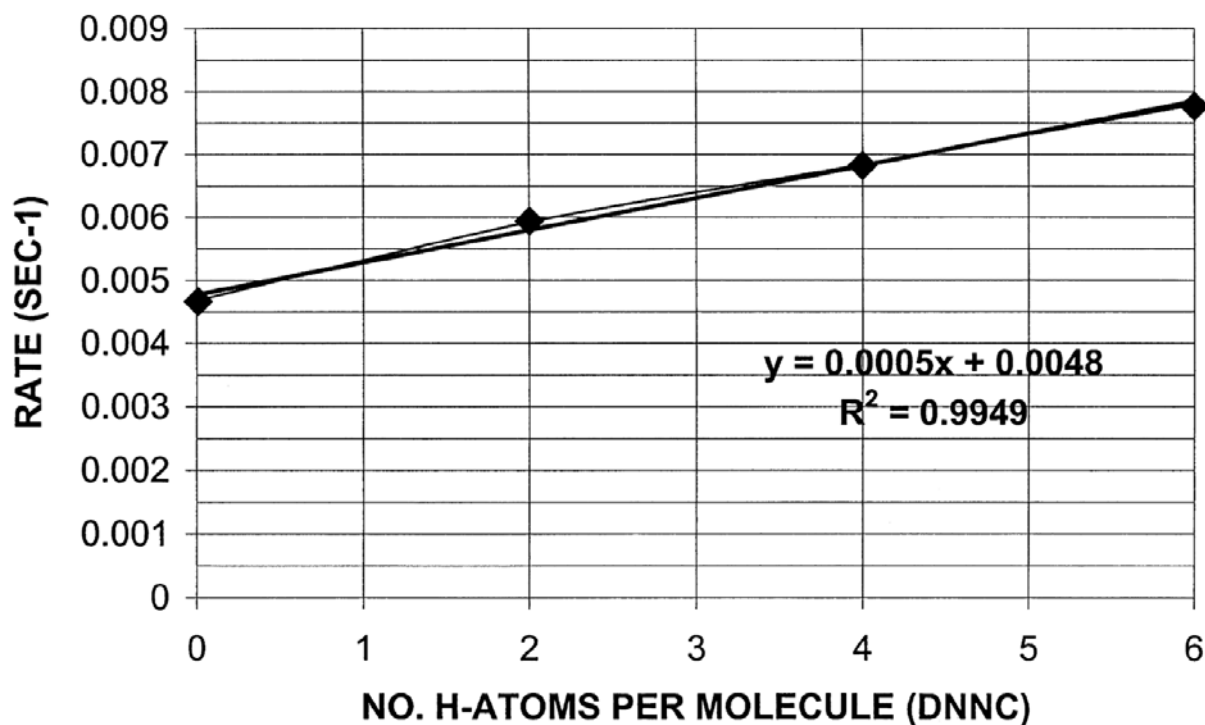


Figure 13. Experimental DNNC isotopomer rate constant versus number of methylene hydrogen atoms in DNNC molecular structure.

RATE CHANGE VS. DNNC D-ATOM INCORPORATION

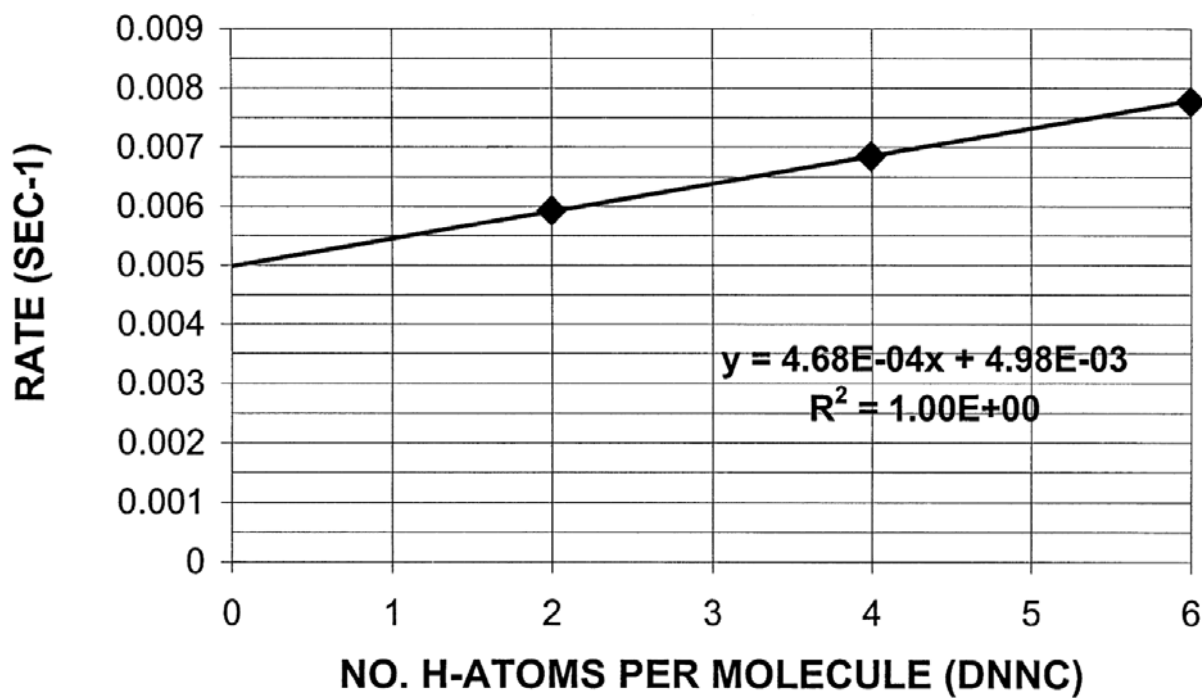


Figure 14. Experimental DNNC isotopomer rate constant versus number of methylene hydrogen atoms in DNNC molecular structure with DNNC-d₆ (H = 0 atoms) isotopomer rate constant not plotted.

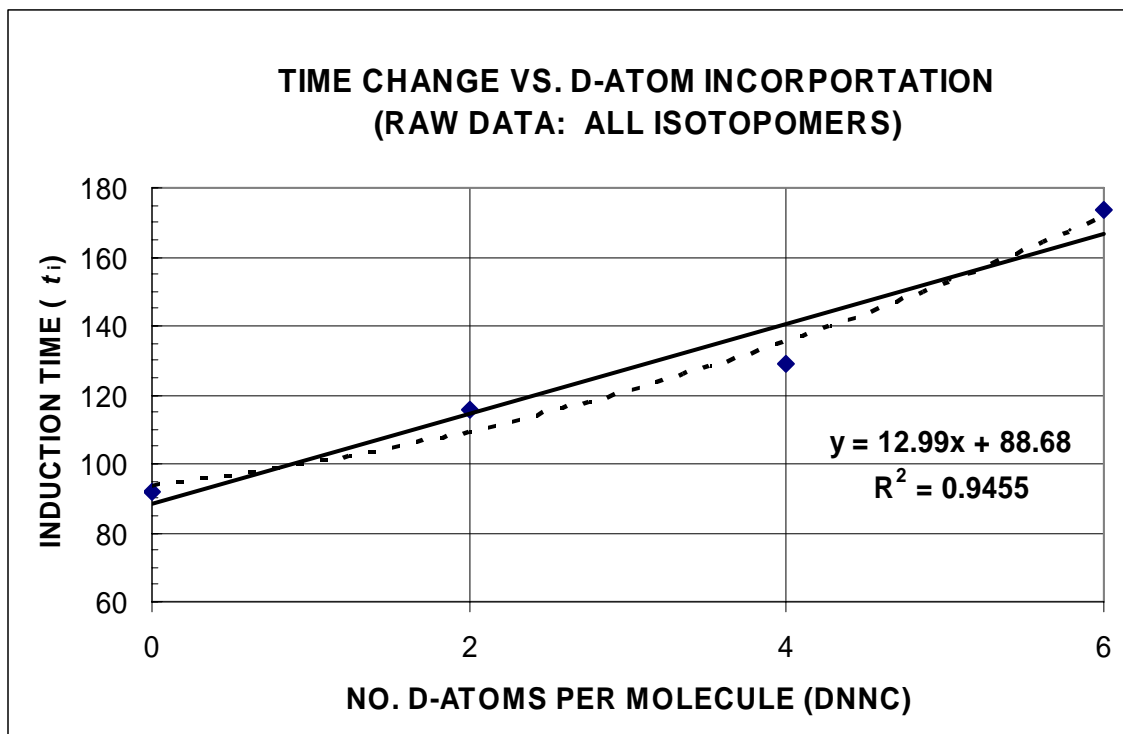


Figure 15. Experimental DNNC isotopomer induction period times versus number of methylene deuterium atoms in DNNC molecular structure.

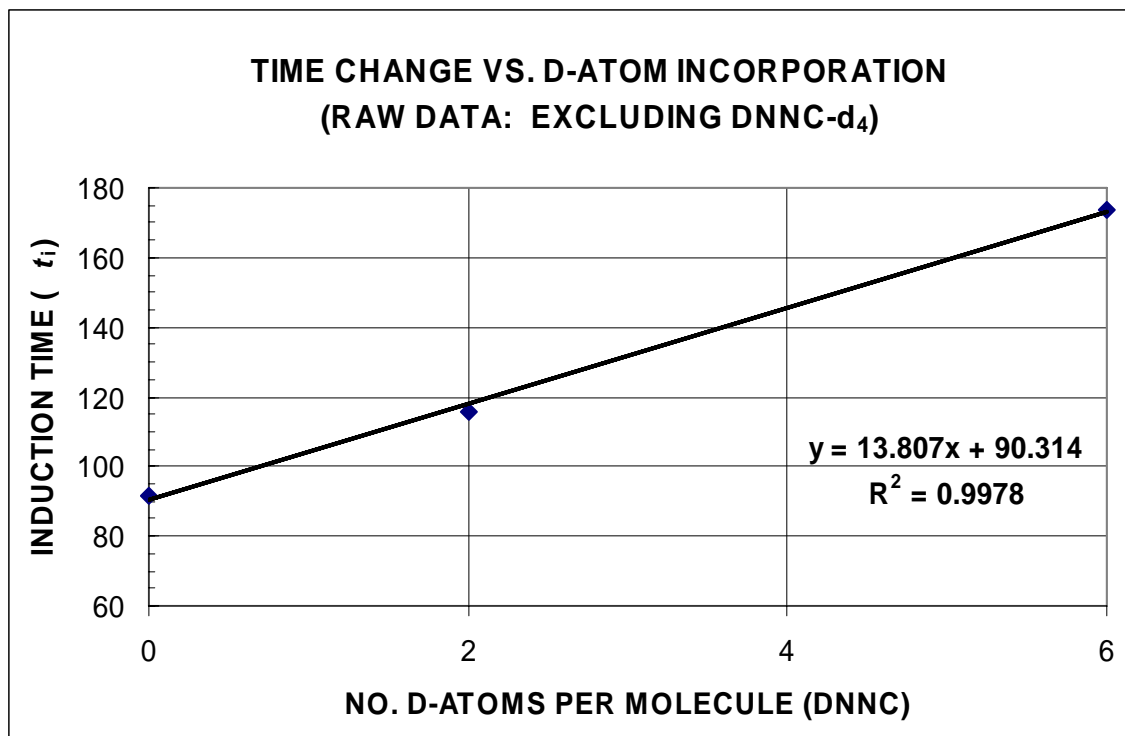


Figure 16. Experimental DNNC isotopomer induction period time versus number of methylene deuterium atoms in DNNC molecular structure with DNNC-d₄ isotopomer induction time not plotted.

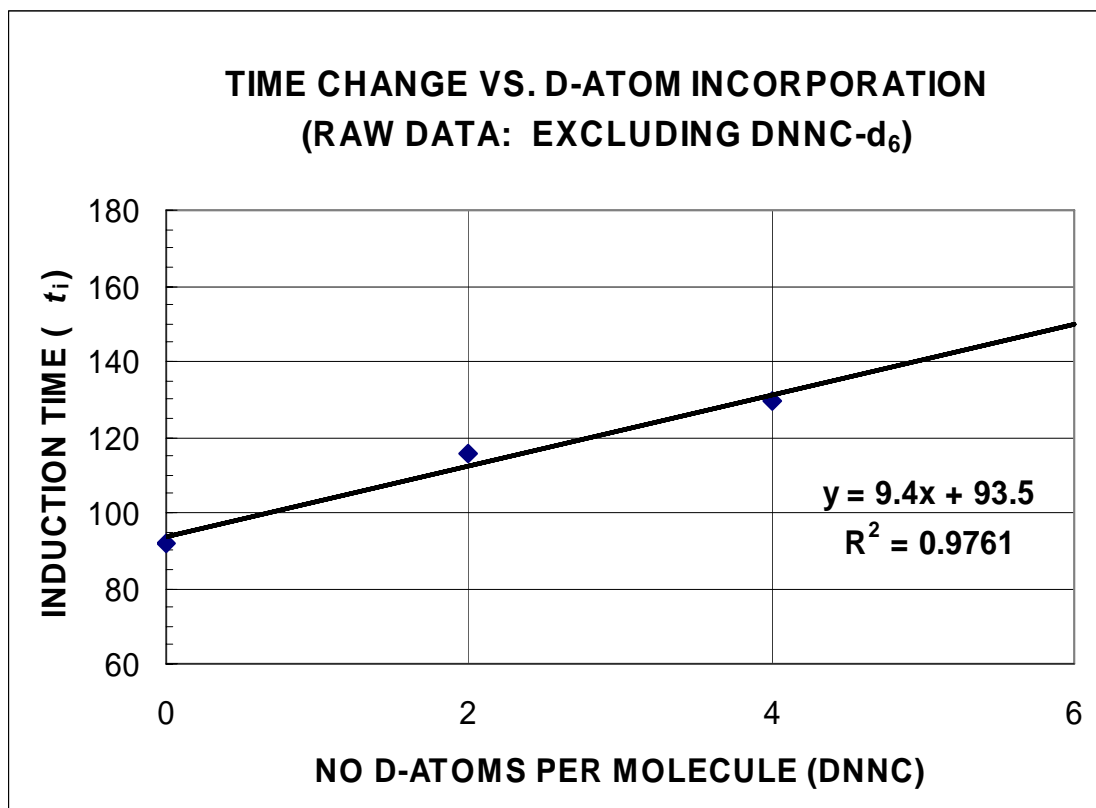


Figure 17. Experimental DNNC isotopomer induction period time versus number of methylene deuterium atoms in DNNC molecular structure with DNNC-d₆ isotopomer induction time not plotted.

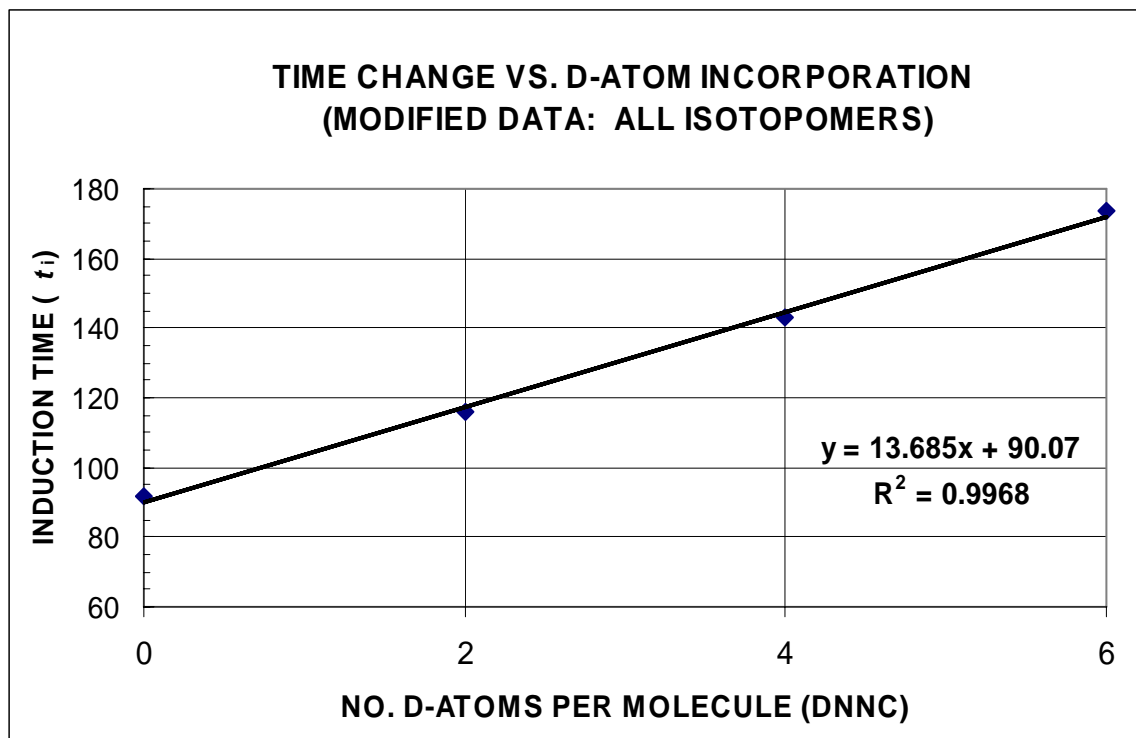


Figure 18. Experimental DNNC isotopomer induction period times versus number of methylene deuterium atoms in DNNC molecular structure with DNNC-d₄ isotopomer modified induction time plotted.

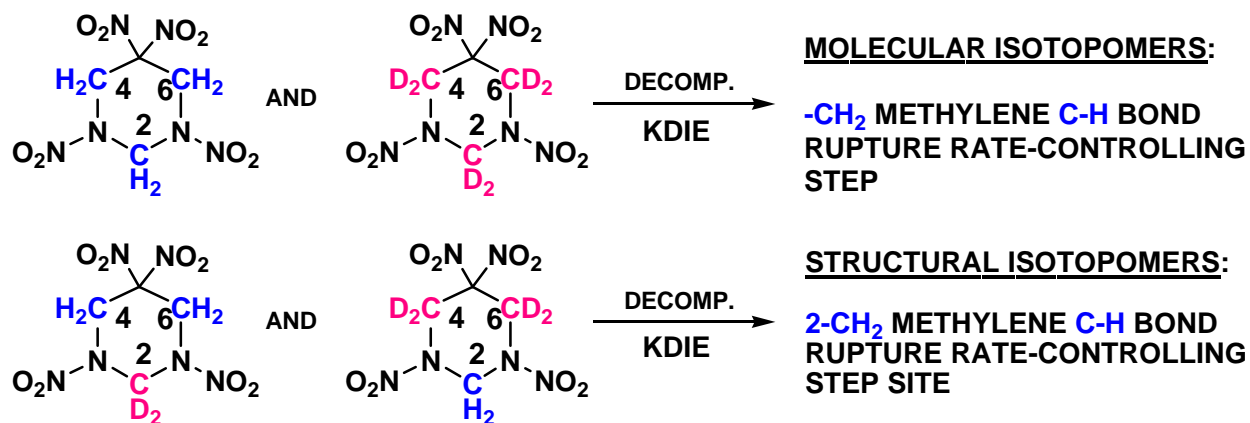


Figure 19. Graphic conclusion for liquid state DNNC thermochemical decomposition findings.